

Measurement of differential cross sections for top quark pair production using the lepton + jets final state in proton-proton collisions at 13 TeV

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Differential and double-differential cross sections for the production of top quark pairs in proton-proton collisions at 13 TeV are measured as a function of jet multiplicity and of kinematic variables of the top quarks and the top quark-antiquark system. This analysis is based on data collected by the CMS experiment at the LHC corresponding to an integrated luminosity of 2.3 fb^{-1} . The measurements are performed in the lepton + jets decay channels with a single muon or electron in the final state. The differential cross sections are presented at particle level, within a phase space close to the experimental acceptance, and at parton level in the full phase space. The results are compared to several standard model predictions.

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I. INTRODUCTION

Studying the differential production cross sections of top quark pairs ($t\bar{t}$) at high energies is a crucial ingredient in testing the standard model and searching for sources of new physics, which could alter the production rate. In particular, the differential $t\bar{t}$ cross sections probe predictions of quantum chromodynamics (QCD) and facilitate the comparisons of the data with state-of-the-art calculations. In addition, some of the measured distributions, especially distributions of invariant mass and rapidity of the $t\bar{t}$ system, can be used to improve our understanding of parton distribution functions (PDFs).

A measurement of the $t\bar{t}$ differential and double-differential production cross sections as a function of jet multiplicity and of kinematic variables of the top quarks and the $t\bar{t}$ system is presented. The measurement is based on proton-proton collision data at a center-of-mass energy of 13 TeV corresponding to an integrated luminosity of 2.3 fb^{-1} [1]. The data were recorded by the CMS experiment at the CERN LHC in 2015. This measurement makes use of the $t\bar{t}$ decay into the $\ell + \text{jets}$ ($\ell = e, \mu$) final state, where, after the decay of each top quark into a bottom quark and a W boson, one of the W bosons decays hadronically and the other one leptonically. The τ lepton decay mode is not considered here as signal. The differential cross sections are presented as a function of the transverse momentum p_T and the absolute rapidity $|y|$ of the hadronically (t_h) and the leptonically (t_ℓ) decaying top quarks, as a function of p_T , $|y|$, and mass M of the $t\bar{t}$ system. The cross section is also measured as a function

of the number of additional jets in the event. In addition, the differential cross sections as a function of $p_T(t_h)$ and $p_T(t\bar{t})$ are measured in bins of jet multiplicity and double-differential cross sections for the following combinations of variables are determined: $|y(t_h)|$ vs $p_T(t_h)$, $M(t\bar{t})$ vs $|y(t\bar{t})|$, and $p_T(t\bar{t})$ vs $M(t\bar{t})$.

This measurement continues a series of differential $t\bar{t}$ production cross section measurements in proton-proton collisions at the LHC. Previous measurements at 7 [2,3] and 8 TeV [4–8] have been performed in various $t\bar{t}$ decay channels.

The differential cross sections are presented in two different ways, at particle level and at parton level. For the particle-level measurement a proxy of the top quark is defined based on experimentally accessible quantities like jets, which consist of quasistable particles with a mean lifetime greater than 30 ps. These are described by theoretical calculations that, in contrast to pure matrix-element calculations, involve parton shower and hadronization models. These objects are required to match closely the experimental acceptance. A detailed definition is given in Sec. III. Such an approach has the advantage that it reduces theoretical uncertainties in the experimental results by avoiding theory-based extrapolations from the experimentally accessible portion of the phase space to the full range, and from jets to partons. However, such results cannot be compared to parton-level calculations.

For the measurement at parton level, the top quarks are defined directly before decaying into a bottom quark and a W boson. For this analysis the parton-level $t\bar{t}$ system is calculated at next-to-leading order (NLO) and combined with a simulation of the parton shower. No restriction of the phase space is applied for parton-level top quarks.

The experimental signature is the same for both measurements and consists of two jets coming from the hadronization of b quarks (b jets), two jets from a hadronically decaying W boson, a transverse momentum imbalance associated with the neutrino, and a single isolated muon or electron.

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This paper is organized as follows: In Sec. II we provide a description of the signal and background simulations, followed by the definition of the particle-level top quarks in Sec. III. After a short overview of the CMS detector and the particle reconstruction in Sec. IV, we describe the object and event selections in Secs. V and VI, respectively. Section VII contains a detailed description of the reconstruction of the $t\bar{t}$ system. Details on the background estimation and the unfolding are presented in Secs. VIII and IX. After a discussion on systematic uncertainties in Sec. X, the results are finally presented in Sec. XI.

II. SIGNAL AND BACKGROUND MODELING

The Monte Carlo programs POWHEG [9–12] (v2) and MADGRAPH5_aMC@NLO [13] (v2.2.2) (MG5_aMC@NLO) are used to simulate $t\bar{t}$ events. They include NLO QCD matrix element calculations that are combined with the parton shower simulation of PYTHIA [14,15] (v8.205) (PYTHIA8) using the tune CUETP8M1 [16]. In addition, MG5_aMC@NLO is used to produce simulations of $t\bar{t}$ events with additional partons. In one simulation all processes of up to three additional partons are calculated at leading order (LO) and combined with the PYTHIA8 parton shower simulation using the MLM [17] algorithm. In another simulation all processes of up to two additional partons are calculated at NLO and combined with the PYTHIA8 parton shower simulation using the FxFx [18] algorithm. The default parametrization of the PDF used in all simulations is NNPDF30_nlo_as_0118 [19]. A top quark mass $m_t = 172.5$ GeV is used. When compared to the data, simulations are normalized to an inclusive $t\bar{t}$ production cross section of 832^{+40}_{-46} pb [20]. This value is calculated with next-to-NLO (NNLO) precision including the resummation of next-to-next-to-leading-logarithmic (NNLL) soft gluon terms. Its given uncertainty is due to the choice of hadronization/factorization scales and PDF.

In all simulations, event weights are calculated that represent the usage of the uncertainty eigenvector sets of the PDF. There are also event weights available that represent the changes of factorization and renormalization scales by a factor of 2 or one half. These additional weights allow for the calculation of systematic uncertainties due to the PDF and the scale choices. For additional uncertainty estimations we use POWHEG + PYTHIA8 simulations with top quark masses of 171.5 and 173.5 GeV, with parton shower scales varied up and down by a factor of 2, and a simulation with POWHEG combined with HERWIG++ [21] (v2.7.1) using the tune EE5C [22].

The main backgrounds are produced using the same techniques. The MG5_aMC@NLO generator is used for the simulation of W boson production in association with jets, t -channel single top quark production, and Drell–Yan (DY) production in association with jets. The POWHEG generator is used for the simulation of single top quark associated production with a W boson (tW) and PYTHIA8 is used for

multijet production. In all cases the parton shower and the hadronization are described by PYTHIA8. The W boson and DY backgrounds are normalized to their NNLO cross sections [23]. The single top quark processes are normalized to NLO calculations [24,25], and the multijet simulation is normalized to the LO calculation [15].

The detector response is simulated using GEANT4 [26]. Afterwards, the same reconstruction algorithms that are applied to the data are used. Multiple proton-proton interactions per bunch crossing (pileup) are included in the simulation. To correct the simulation to be in agreement with the pileup conditions observed during the data taking, the average number of pileup events per bunch crossing is calculated for the measured instantaneous luminosity. The simulated events are weighted, depending on their number of pileup interactions, to reproduce the measured pileup distribution.

III. PARTICLE-LEVEL TOP QUARK DEFINITION

The following list describes the definitions of objects constructed from quasistable particles, obtained from the predictions of $t\bar{t}$ event generators before any detector simulation. These objects are further used to define the particle-level top quarks.

- (i) Muons and electrons that do not have their origin in a decay of a hadron are selected and their momenta are corrected for the final-state radiation effects. The anti- k_T jet algorithm [27,28] with a distance parameter of 0.1 is used to cluster the leptons and photons not originating from hadron decays. Those photons that are clustered together with a selected lepton are assumed to have been radiated by the lepton and their momenta are added to the lepton momentum. However, the lepton is only selected if the original p_T is at least half of their corrected p_T .
- (ii) All neutrinos that do not have their origin in a decay of a hadron are selected.
- (iii) Jets are clustered by the anti- k_T jet algorithm with a distance parameter of 0.4. All quasistable particles are considered, excluding the selected neutrinos and leptons together with their radiated photons.
- (iv) b jets at particle level are defined as those jets that contain a b hadron. As a result of the short lifetime of b hadrons, only their decay products should be considered for the jet clustering. However, to allow their association to a jet, the b hadrons are also included with their momenta scaled down to a negligible value. This preserves the information of their directions, but they have no impact on the jet clustering itself.

Based on the invariant masses M of these objects, we construct a pair of particle-level top quarks in the $\ell + \text{jets}$ final state. Events with exactly one muon or electron with $p_T > 30$ GeV and an absolute pseudorapidity $|\eta| < 2.5$ are selected. We take the sum of the four-momenta of all

selected neutrinos as the neutrino momentum p_ν from the leptonically decaying top quark and find the permutation of jets that minimizes the quantity

$$K^2 = [M(p_\nu + p_\ell + p_{b_\ell}) - m_t]^2 + [M(p_{j_1} + p_{j_2}) - m_W]^2 + [M(p_{j_1} + p_{j_2} + p_{b_h}) - m_t]^2, \quad (1)$$

where $p_{j_{1/2}}$ are the four-momenta of two light-flavor jet candidates, $p_{b_{\ell/h}}$ are the four-momenta of two b -jet candidates, p_ℓ is the four-momentum of the lepton, and $m_W = 80.4$ GeV is the mass of the W boson. All jets with $p_T > 25$ GeV and $|\eta| < 2.5$ are considered. At least four jets are required, of which at least two must be b jets. If there are more than two b jets, we allow b jets as decay

products of the proxy for the hadronically decaying W boson. Due to a limited efficiency of the b -jet identification at detector level this improves the agreement between the reconstructed top quarks and the particle-level top quarks. The remaining jets with the same kinematic selection are considered as additional jets at particle level.

It should be remarked that events with a hadronic and a leptonic particle-level top quark are not required to be ℓ + jets events at the parton level. As an example, in Fig. 1 the relation between the $p_T(t_h)$ values at particle and parton level is shown.

IV. THE CMS DETECTOR

The central feature of the CMS detector is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two end cap sections. Forward calorimeters extend the η coverage provided by the barrel and end cap detectors. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. A more detailed description of the CMS detector, together with a definition of the coordinate system and relevant kinematic variables, can be found in Ref. [29].

The particle-flow (PF) event algorithm [30,31] reconstructs and identifies each individual particle with an optimized combination of information from the various elements of the CMS detector. The energy of photons is directly obtained from the ECAL measurement, corrected for zero-suppression effects. The energy of electrons is determined from a combination of the electron momentum at the primary interaction vertex as determined by the tracker, the energy of the corresponding ECAL cluster, and the energy sum of all bremsstrahlung photons spatially compatible with originating from the electron track. The energy of muons is obtained from the curvature of the corresponding track. The energy of charged hadrons is determined from a combination of their momentum measured in the tracker and the matching ECAL and HCAL energy deposits, corrected for zero-suppression effects and for the response function of the calorimeters to hadronic showers. Finally, the energy of neutral hadrons is obtained from the corresponding corrected ECAL and HCAL energy.

V. PHYSICS OBJECT RECONSTRUCTION

This analysis depends on the reconstruction and identification of muons, electrons, jets, and missing transverse momentum associated with a neutrino. Only leptons are selected that are compatible with originating from the primary vertex, defined as the vertex at the beam position with the highest sum of p_T^2 of the associated tracks. Leptons

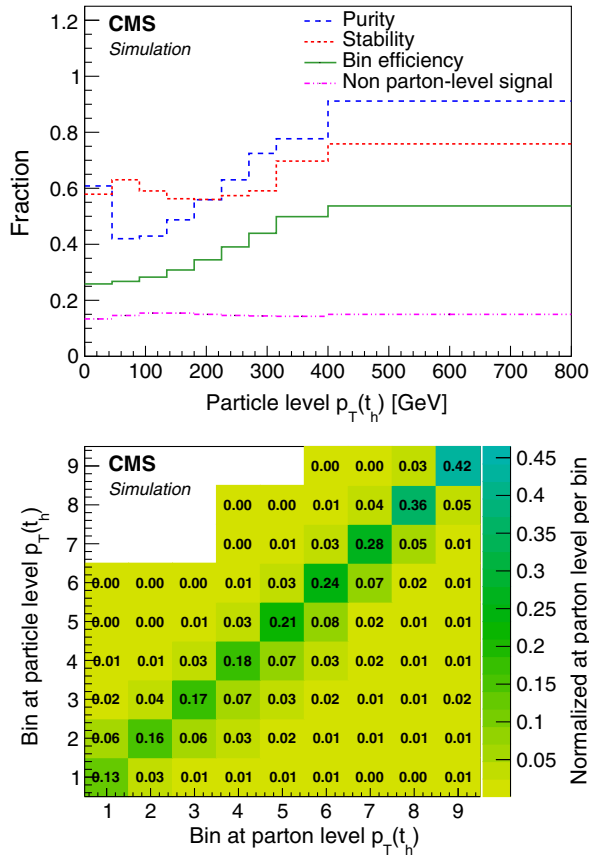


FIG. 1. Comparison between the $p_T(t_h)$ at particle and parton level, extracted from the POWHEG+PYTHIA8 simulation. Left: fraction of parton-level top quarks in the same bin at particle level (purity), fraction of particle-level top quarks in the same bin at parton level (stability), ratio of the number of particle- to parton-level top quarks, and fraction of events with a particle-level top quark pair that are not considered as signal events at parton level. Right: bin migrations between particle and parton level. The p_T range of the bins can be taken from the left panel. Each column is normalized to the number of events per column at parton level in the full phase space.

from $t\bar{t}$ decays are typically isolated, i.e., separated in $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$ from other particles. A requirement on the lepton isolation is used to reject leptons produced in decays of hadrons.

The muon isolation variable is defined as the sum of the p_T of all tracks, except for the muon track, originating from the $t\bar{t}$ interaction vertex within a cone of $\Delta R = 0.3$. It is required to be less than 5% of the muon p_T . The muon reconstruction and selection [32] efficiency is measured in the data using tag-and-probe techniques [33]. Depending on the p_T and η of the muon it is 90%–95%.

For electrons the isolation variable is the sum of the p_T of neutral hadrons, charged hadrons, and photon PF candidates in a cone of $\Delta R = 0.3$ around the electron. Contributions of the electron to the isolation variable are suppressed excluding a small region around the electron. This isolation variable is required to be smaller than 7% of the electron p_T . An event-by-event correction is applied that maintains a constant electron isolation efficiency with respect to the number of pileup interactions [34]. The measured reconstruction and identification [35] efficiency for electrons is 70%–85% with a p_T and η dependence.

Jets are reconstructed from PF objects clustered using the anti- k_T jet algorithm with a distance parameter of 0.4 using the FASTJET package [28]. Charged particles originating from a vertex of a pileup interaction are excluded. The total energy of the jets is corrected for energy depositions from pileup. In addition, p_T —and η -dependent corrections are applied to correct for detector response effects [36]. Those jets identified as isolated muons or electrons are removed from consideration.

For the identification of b jets the combined secondary vertex algorithm [37] is used. It provides a discriminant between light-flavor and b jets based on the combined information of secondary vertices and the impact parameter of tracks at the primary vertex. A jet is identified as b jet if the associated value of the discriminant exceeds a threshold criterion. Two threshold criteria are used: a tight threshold with an efficiency of about 70% and a light-flavor jet rejection probability of 95%, and a loose one with an efficiency of about 80% and a rejection probability of 85%.

The missing transverse momentum \vec{p}_T^{miss} is calculated as the negative of the vectorial sum of transverse momenta of all PF candidates in the event. Jet energy corrections are also propagated to improve the measurement of \vec{p}_T^{miss} .

VI. EVENT SELECTION

Events are selected if they pass single-lepton triggers. These require $p_T > 22$ GeV for electrons and $p_T > 20$ GeV for muons, as well as various quality and isolation criteria.

To reduce the background contributions and optimize the $t\bar{t}$ reconstruction additional, more stringent, requirements on the events are imposed. Events with exactly one muon or

electron with $p_T > 30$ GeV and $|\eta| < 2.1$ are selected. No additional muons or electrons with $p_T > 15$ GeV and $|\eta| < 2.4$ are allowed. In addition to the lepton, at least four jets with $p_T > 30$ GeV and $|\eta| < 2.4$ are required. At least two of these jets must be tagged as b jets. At least one jet has to fulfil the tight b -jet identification criterion while for the second b jet only the loose criterion is required. At least one of the two jets with the highest value of the b -tagging discriminant and at least one of the remaining jets is required to have $p_T > 35$ GeV.

We compare several kinematic distributions of the muon and electron channels to the simulation to verify that there are no unexpected differences. The ratios of the measured to the expected event yields in the two channels agree within the uncertainty in the lepton reconstruction and selection efficiencies. In the remaining steps of the analysis the two channels are combined by adding their distributions.

VII. RECONSTRUCTION OF THE TOP QUARK-ANTIQUARK SYSTEM

The goal of the $t\bar{t}$ reconstruction is the correct identification of reconstructed objects as parton- or particle-level top quark decay products. To test the performance of the reconstruction algorithm an assignment between detector level and particle- (parton-) level objects is needed. For the particle-level measurement this relationship is straightforward. Reconstructed leptons and jets can be matched spatially to corresponding objects at the particle level. For the parton-level measurement we need to define how to match the four initial quarks from a $t\bar{t}$ decay with reconstructed jets. This is not free of ambiguities since a quark does generally not lead to a single jet. One quark might shower into several jets or multiple quarks might be clustered into one jet if they are not well separated. We introduce an unambiguous matching criterion that matches the reconstructed jet with the highest p_T within $\Delta R = 0.4$ to a quark from the $t\bar{t}$ decay. If two quarks are matched with the same jet, the event has a merged topology and is considered as “not reconstructible” in the context of this analysis.

The same matching criterion is also used to assign particle-level jets to the $t\bar{t}$ decay products at parton level. Those particle-level jets with $p_T > 25$ GeV and $|\eta| < 2.5$, which are not assigned to one of the initial quarks, are considered as additional jets at parton level.

For the reconstruction of the top quark-antiquark system all possible permutations of jets that assign reconstructed jets to the decay products of the $t\bar{t}$ system are tested and a likelihood that a certain permutation is correct is evaluated. Permutations are considered only if the two jets with the highest b -tagging probabilities are the two b -jet candidates. In addition, the p_T of at least one b -jet candidate and at least one jet candidate from the W boson decay have to be above 35 GeV. In each event the permutation with the highest probability is selected. The likelihoods are

evaluated separately for the particle- and the parton-level measurements.

The first reconstruction step involves the determination of the neutrino four-momentum p_ν . This is performed using the algorithm described in Ref. [38]. The idea is to find all possible solutions for the three components of the neutrino momentum using the two mass constraints $(p_\nu + p_\ell)^2 = m_W^2$ and $(p_\nu + p_\ell + p_{b_\ell})^2 = m_t^2$. Each equation describes an ellipsoid in the three-dimensional momentum space of the neutrino. The intersection of these two ellipsoids is usually an ellipse. We select p_ν as the point on the ellipse for which the distance $D_{\nu,\min}$ between the ellipse projection onto the transverse plane and \vec{p}_T^{miss} is minimal. This algorithm leads to a unique solution for the longitudinal neutrino momentum and an improved resolution for the transverse component. The minimum distance $D_{\nu,\min}$ can also be used to identify the correct b_ℓ . In the cases with an invariant mass of the lepton and the b_ℓ candidate above m_t no solution can be found and we continue with the next permutation.

The likelihood λ is maximized to select the best permutation of jets. It uses constraints of the top quark and W boson masses on the hadronic side and the $D_{\nu,\min}$

value from the neutrino reconstruction, and is defined through

$$-\log(\lambda) = -\log(P_m(m_2, m_3)) - \log(P_\nu(D_{\nu,\min})), \quad (2)$$

where P_m is the two-dimensional probability distribution of the invariant masses of correctly reconstructed W bosons and top quarks. This probability is calculated for the invariant mass of the two jets m_2 tested as the W boson decay products, and the invariant mass of the three jets m_3 tested as the decay products of the hadronically decaying top quark. The distributions for the correct jet assignments, taken from the POWHEG+PYTHIA8 simulation and normalized to unity, are shown in Fig. 2 for the particle- and parton-level measurements. Permutations with probabilities of less than 0.1% of the highest value are rejected. This part of the likelihood is sensitive to the correct reconstruction of the hadronically decaying top quark, modulo a permutation of the two jets from the W boson, but none of the measured kinematic variables are affected by this ambiguity.

The probability P_ν describes the distribution of $D_{\nu,\min}$ for a correctly selected b_ℓ . In Fig. 2 the normalized distributions of $D_{\nu,\min}$ for b_ℓ and for other jets are shown.

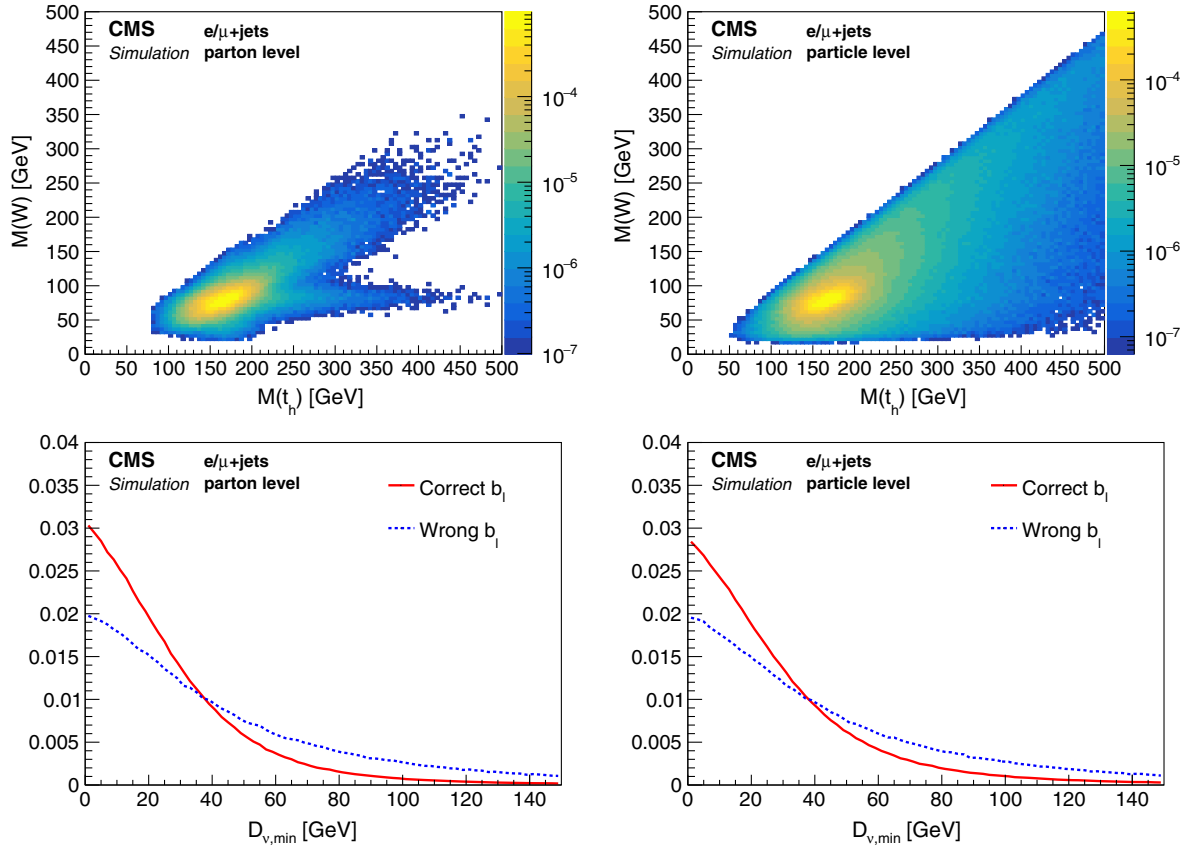


FIG. 2. Top: normalized two-dimensional mass distribution of the correct reconstructed hadronically decaying W bosons $M(W)$ and the correct reconstructed top quarks $M(t_h)$ for the parton- (left) and the particle- (right) level measurements. Bottom: normalized distributions of the distance $D_{\nu,\min}$ for correctly and wrongly selected b jets from the leptonically decaying top quarks. The distributions are taken from the POWHEG+PYTHIA8 $t\bar{t}$ simulation.

On average, the distance $D_{\nu,\min}$ for correctly selected b_ℓ is smaller and has a lower tail compared to the distance obtained for other jets. Permutations with values of $D_{\nu,\min} > 150$ GeV are rejected since they are very unlikely to originate from a correct b_ℓ association. This part of the likelihood is sensitive to the correct reconstruction of the leptonically decaying top quark.

The likelihood λ combines the probabilities from the reconstruction of the hadronically and leptonically decaying top quarks and provides information on reconstructing the whole $t\bar{t}$ system. The performance of the reconstruction algorithm is tested using the three $t\bar{t}$ simulations generated with POWHEG combined with PYTHIA8 or HERWIG++, and MG5_aMC@NLO+PYTHIA8 where we use the input distributions P_m and P_ν from POWHEG+PYTHIA8. The efficiency of the reconstruction algorithm is defined as the probability that the most likely permutation, as identified through the maximization of the likelihood λ , is the correct one, given that all decay products from the $t\bar{t}$ decay are reconstructed and selected. These efficiencies as a function

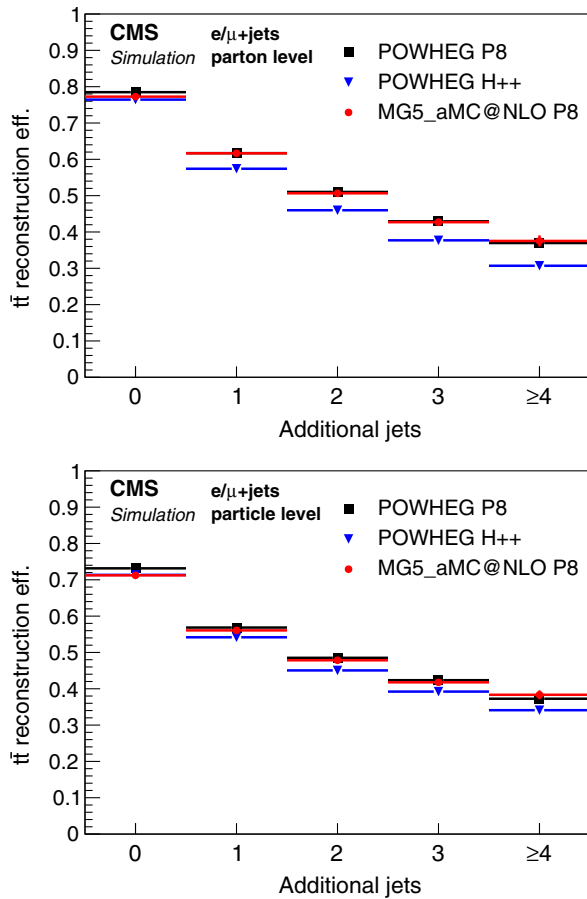


FIG. 3. Reconstruction efficiency of the $t\bar{t}$ system as a function of the number of additional jets for the parton- (left) and particle- (right) level measurements calculated based on the simulations with POWHEG+PYTHIA8 (P8), POWHEG+HERWIG++ (H++), and MG5_aMC@NLO +PYTHIA8.

of the jet multiplicity are shown in Fig. 3. Since the number of permutations increases drastically with the number of jets, it is more likely to select a wrong permutation if there are additional jets. The small differences observed in different simulations are taken into account for the uncertainty estimations. We observe a lower reconstruction efficiency for the particle-level measurement. This is caused by the weaker mass constraints for a particle-level top quark, where, in contrast to the parton-level top quark, exact matches to the top quark and W boson masses are not required. This can be seen in the mass distributions of Fig. 2 and the likelihood distributions in Fig. 4. Here the signal simulation is divided into the following categories: correctly reconstructed $t\bar{t}$ systems ($t\bar{t}$ right reco), events where all decay products are available, but the algorithm failed to

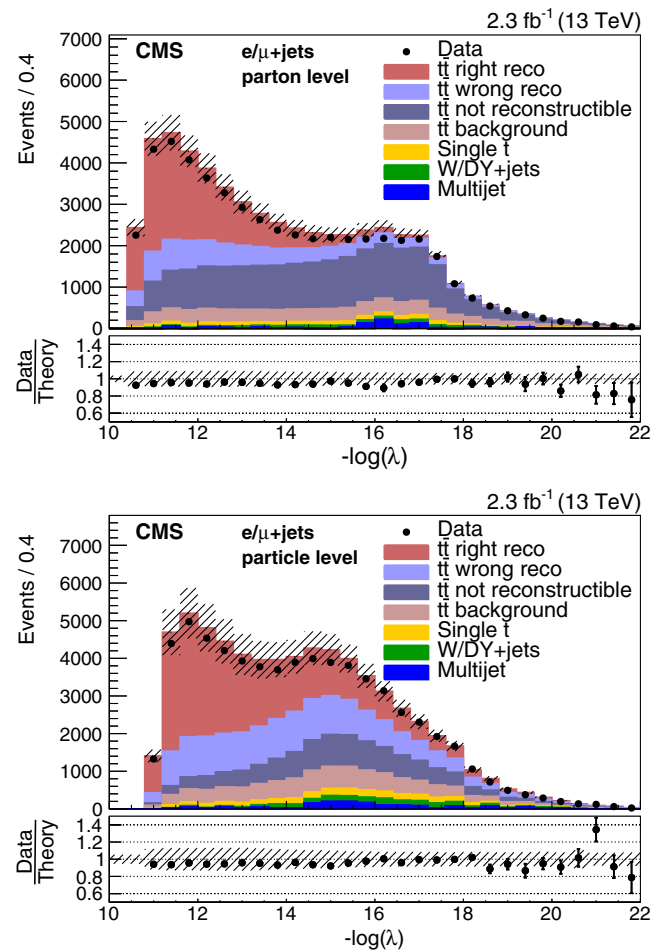


FIG. 4. Distribution of the negative log likelihood for the selected best permutation in the parton- (left) and the particle- (right) level measurements in data and simulations. The simulation of POWHEG+PYTHIA8 is used to describe the $t\bar{t}$ production. Experimental (cf. Sec. X) and statistical uncertainties (hatched area) are shown for the total simulated yield, which is normalized to the measured integrated luminosity. The ratios of data to the sum of the expected yields are provided at the bottom of each panel.

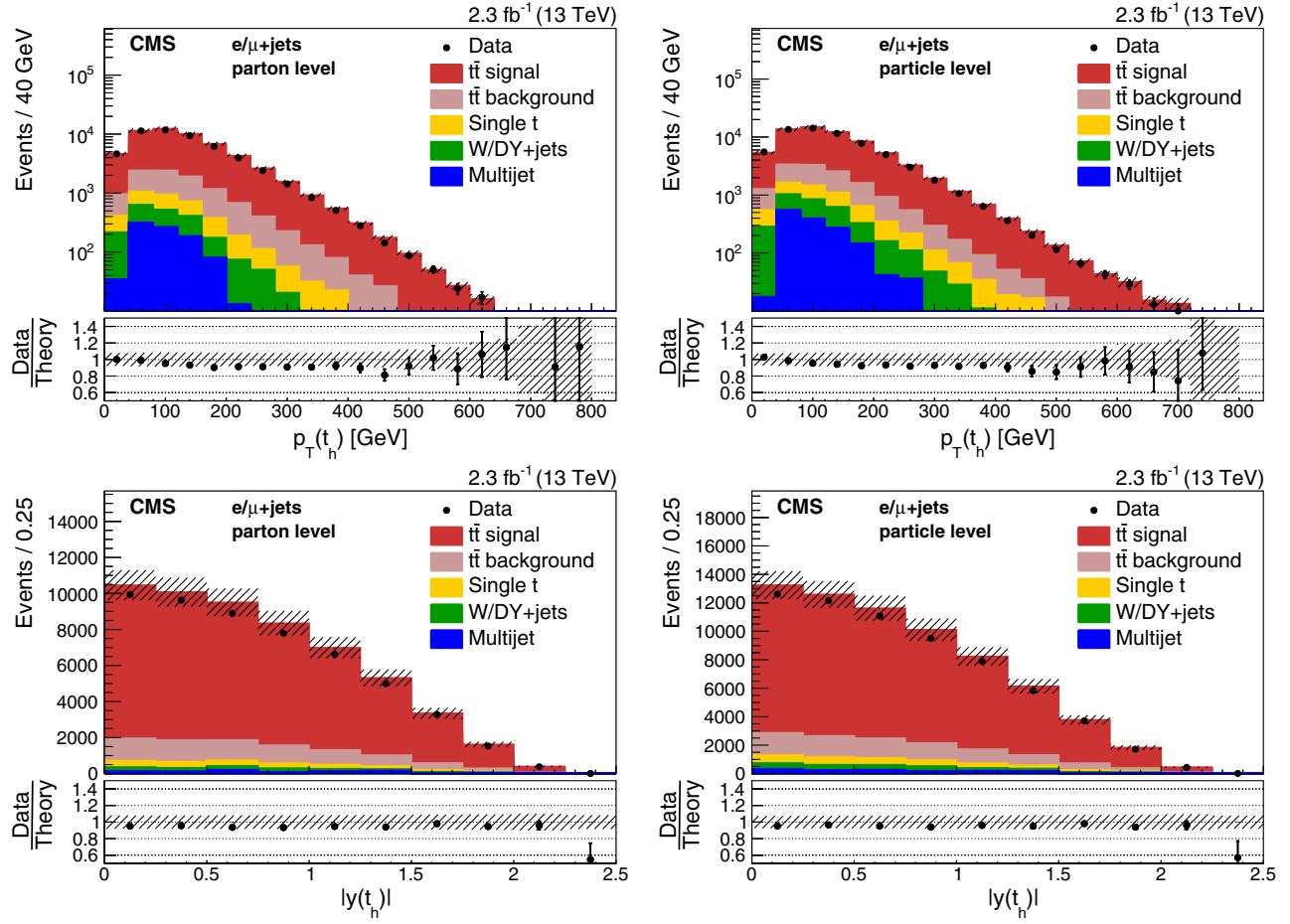


FIG. 5. Comparisons of the reconstructed $p_T(t_h)$ (top) and $|y(t_h)|$ (bottom) in data and simulations for the parton (left) and the particle (right) level. The simulation of POWHEG+PYTHIA8 is used to describe the $t\bar{t}$ production. Experimental (cf. Sec. X) and statistical uncertainties (hatched area) are shown for the total simulated yield, which is normalized according to the measured integrated luminosity. The ratios of data to the expected yields are given at the bottom of each panel.

identify the correct permutation ($t\bar{t}$ wrong reco), $\ell + \text{jets } t\bar{t}$ events where at least one decay product is missing ($t\bar{t}$ not reconstructible), and nonsignal $t\bar{t}$ events ($t\bar{t}$ background). However, the lower reconstruction efficiency of the particle-level top quark is compensated by the higher number of reconstructible events.

In Fig. 5 the distributions of p_T and $|y|$ of the reconstructed hadronically decaying top quarks for the parton- and particle-level measurements are compared to the simulation. In Fig. 6 the distributions of $p_T(t\bar{t})$, $|y(t\bar{t})|$, $M(t\bar{t})$, and the number of additional jets are shown. In general, good agreement is observed between the data and the simulation though the overall yield in the data is slightly lower, but within the experimental uncertainties. The observed jet multiplicities are lower than predicted.

VIII. BACKGROUND SUBTRACTION

After the event selection and $t\bar{t}$ reconstruction about 65 000 (53 000) events are observed in the particle- (parton-) level measurements. A small contribution of

about 9% of single top quark, DY, W boson, and multijet events is expected. These have to be estimated and subtracted from the selected data.

The background from single top quark production is subtracted based on its simulation. Its overall contribution corresponds to about 4% of the selected data. Single top quark production cross sections are calculated with precisions of a few percent [24,25]. Since the calculations have a limited reliability after $t\bar{t}$ selection we assume an overall uncertainty of 50%. However, this conservative estimate has negligible impact on the final results and their accuracy.

The simulations of multijet, DY, and W boson production contain limited numbers of events after the full selection. We extract the shapes of the distributions of these backgrounds from a control region in the data, similar to the signal region, but requiring no b -tagged jet in the event. In this selection the contribution of $t\bar{t}$ events is estimated to be about 15%. The remaining fraction consists of multijet, DY, and W boson events. The reconstruction algorithm is exactly the same as for the signal selection. To estimate the shape dependency in the control region on the

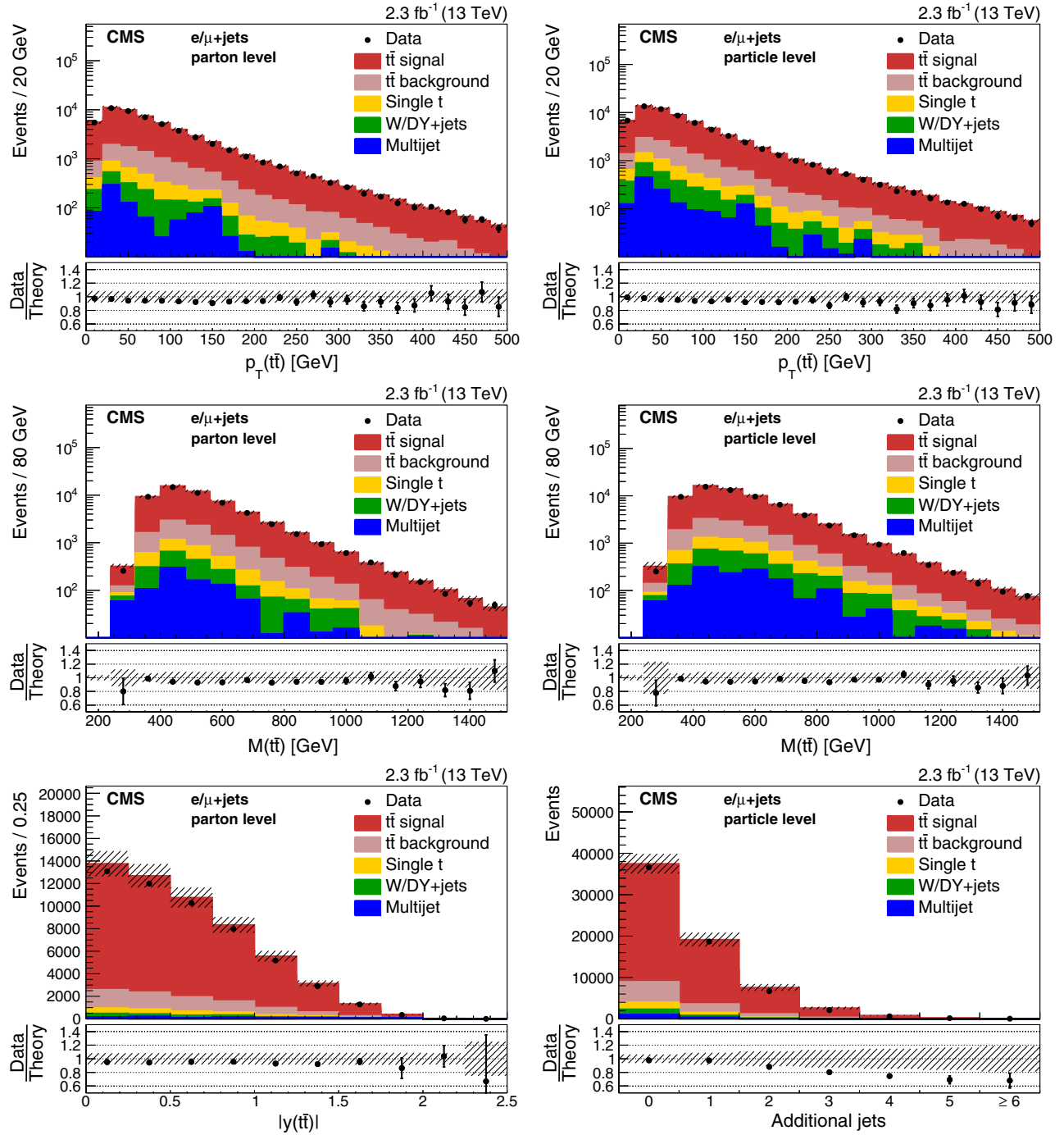


FIG. 6. Comparisons of the reconstructed distributions of $p_T(\bar{t}t)$ (top) and $M(\bar{t}t)$ (middle) for the parton- (left) and the particle- (right) level measurements in data and simulations. Bottom: distributions of $|y(\bar{t}t)|$ (left) and the number of additional jets (right). The simulation of POWHEG+PYTHIA8 is used to describe the $\bar{t}t$ production. Experimental (cf. Sec. X) and statistical uncertainties (hatched area) are shown for the total simulated yield, which is normalized according to the measured integrated luminosity. The ratios of data to the expected yields are given at the bottom of each panel.

selection we vary the selection threshold of the b -tagging discriminant. This changes the top quark contribution and the flavor composition; however, we find the observed shape variation to be negligible. For the background subtraction, the distributions extracted from the control region are normalized to the yield of multijet, DY, and W

boson events predicted by the simulation in the signal region. In the control region the expected and measured event yields agree within their statistical uncertainties. Taking into account the statistical uncertainty of the normalization factor and the shape differences between the signal and control regions in the simulation, we estimate

TABLE I. Overview of the uncertainties in the differential cross section measurements at particle and at parton level. Typical ranges of uncertainties in the bins are shown.

Source	Particle level	Parton level
Statistical uncertainty	1–5	1–5
Jet energy scale	5–8	6–8
Jet energy resolution	<1	<1
\vec{p}_T^{miss} (nonjet)	<1	<1
b tagging	2–3	2–3
Pileup	<1	<1
Lepton selection	3	3
Luminosity	2.3	2.3
Background	1–3	1–3
PDF	<1	<1
Fact./ren. scale	<1	<1
Parton shower scale	2–5	2–9
POWHEG+PYTHIA8 VS. HERWIG++	1–5	1–12
NLO event generation	1–5	1–10
m_t	1–2	1–3

an overall uncertainty of 20% in this background estimation. The overall contribution to the selected data is about 5%.

For the parton-level measurement, special care has to be taken with the contribution of nonsignal $t\bar{t}$ events, i.e., dilepton, all-jet, and τ + jets events. For the particle-level measurement care is needed with all $t\bar{t}$ events for which no pair of particle-level top quarks exists. The behavior of this background depends on the $t\bar{t}$ cross section and a subtraction according to the expected value can result in a bias of the measurement, especially if large differences between the simulation and the data are observed. However, the shapes of the distributions show an agreement within uncertainties between data and simulation and we subtract the predicted relative fractions from the remaining event yields.

IX. UNFOLDING

For the unfolding, the iterative D'Agostini method [39] is used. The migration matrices and the acceptances are

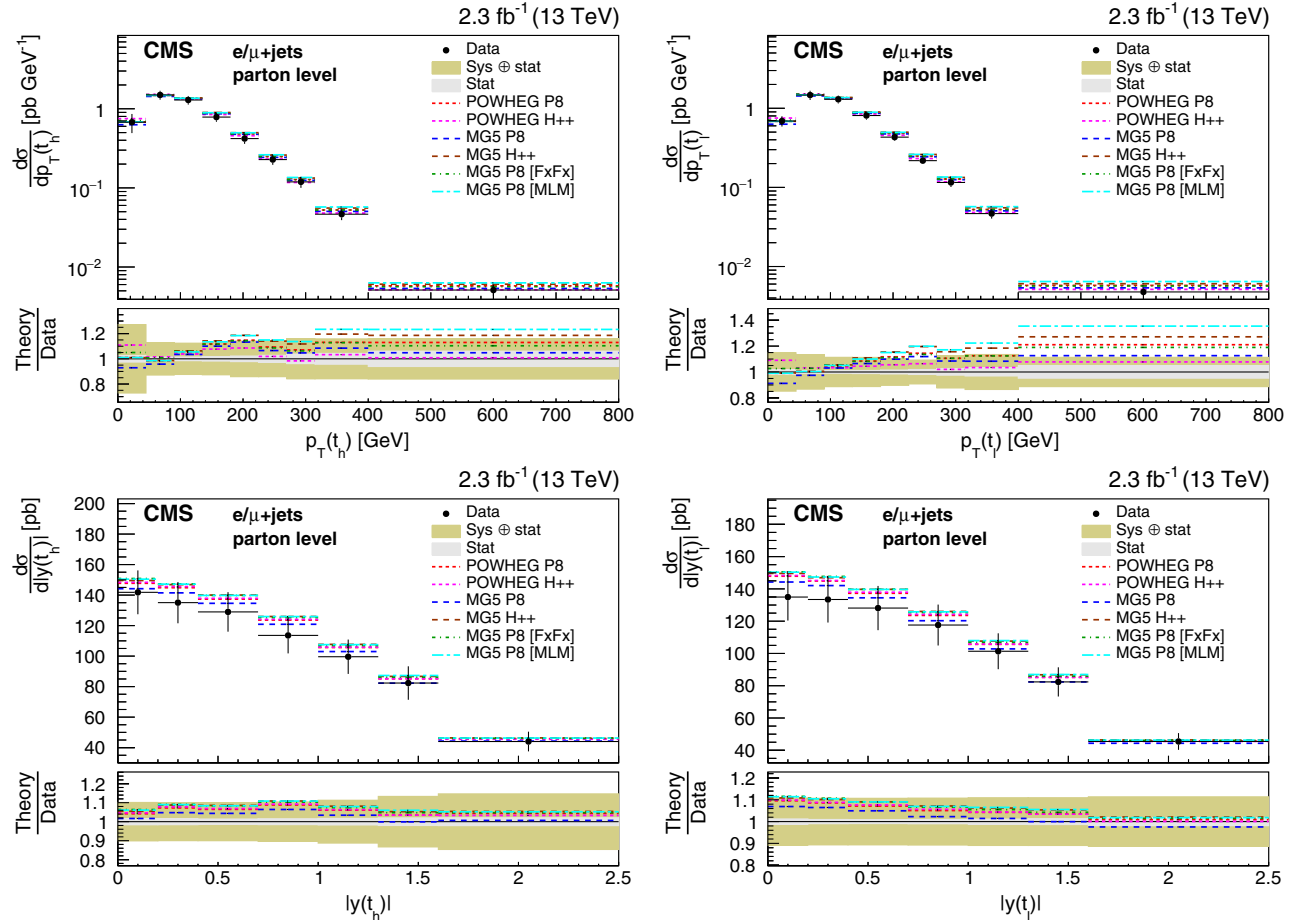


FIG. 7. Differential cross sections at parton level as a function of $p_T(t)$ (top) and $|y(t)|$ (bottom) measured separately for the hadronically (left) and leptonically (right) decaying top quarks. The cross sections are compared to the predictions of POWHEG and MG5_aMC@NLO (MG5) combined with PYTHIA8 (P8) or HERWIG++ (H++) and the multiparton simulations MG5_aMC@NLO +PYTHIA8 MLM and MG5_aMC@NLO +PYTHIA8 FxFx. The ratios of the various predictions to the measured cross sections are shown at the bottom of each panel together with the statistical and systematic uncertainties of the measurement.

needed as input. The migration matrix relates the quantities at particle (parton) level and at detector level. It accounts for the effects from the parton shower and hadronization as well as the detector response, where the former has a large impact on the parton-level measurement. For the central results the migration matrices and the acceptances are taken from the POWHEG+PYTHIA8 simulation and other simulations are used to estimate the uncertainties. The binning in the unfolding is optimized based on the resolution in the simulation. We utilize for the minimal bin widths that, according to the resolution, at least 50% of the events are reconstructed in the correct bin.

The iterative D'Agostini method takes the number of iterations as an input parameter to control the level of regularization. A small number of iterations corresponds to a large regularization, which may bias the unfolded results. The level of regularization and hence the bias decreases with the number of iterations—but with the drawback of

increasing variances in the unfolded spectra. To optimize the number of iterations, we chose the criterion that the compatibility between a model and the unfolded data at particle (parton) level is the same as the compatibility between the folded model and the data at detector level. The compatibilities are determined by χ^2 tests at both levels based on all available simulations and several modified spectra obtained by reweighting the $p_T(t)$, $|y(t)|$, or $p_T(\bar{t})$ distributions in the POWHEG+PYTHIA8 simulation. The reweighted spectra are chosen in such a way that they cover the observed differences between the data and the unmodified simulation.

We find the above criterion fulfilled for the number of iterations such that a second χ^2 test between the detector-level spectrum with its statistical uncertainty and the refolded spectrum exceeds a probability of 99.9%. The refolded spectrum is obtained by inverting the unfolding step. This consists of a multiplication with the response matrix and does not need any regularization.

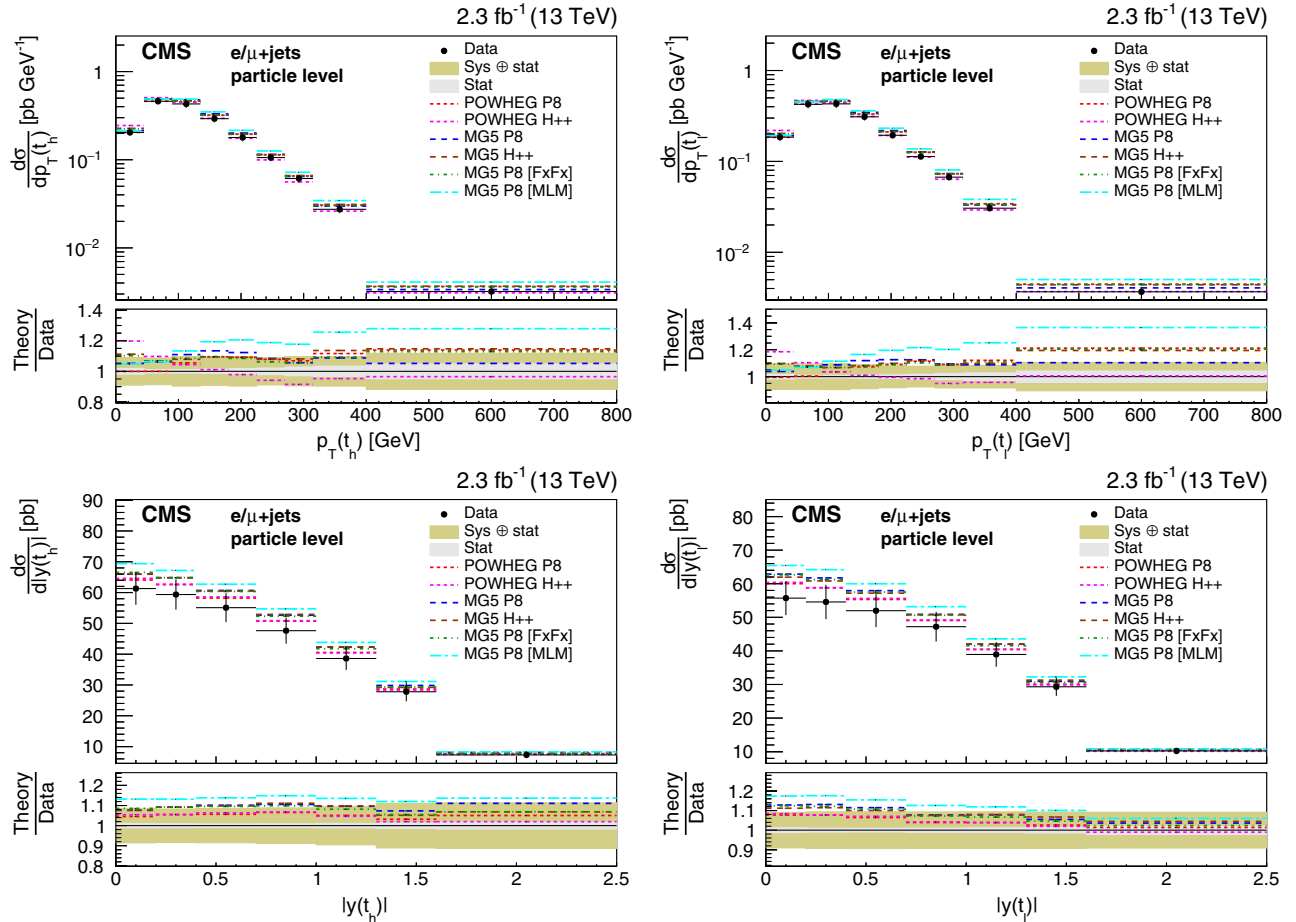


FIG. 8. Differential cross sections at particle level as a function of $p_T(t)$ (top) and $|y(t)|$ (bottom) measured separately for the hadronically (left) and leptonically (right) decaying particle-level top quarks. The cross sections are compared to the predictions of POWHEG and MG5_aMC@NLO (MG5) combined with PYTHIA8 (P8) or HERWIG++ (H++) and the multiparton simulations MG5_aMC@NLO+PYTHIA8 MLM and MG5_aMC@NLO+PYTHIA8 FxFx. The ratios of the various predictions to the measured cross sections are shown at the bottom of each panel together with the statistical and systematic uncertainties of the measurement.

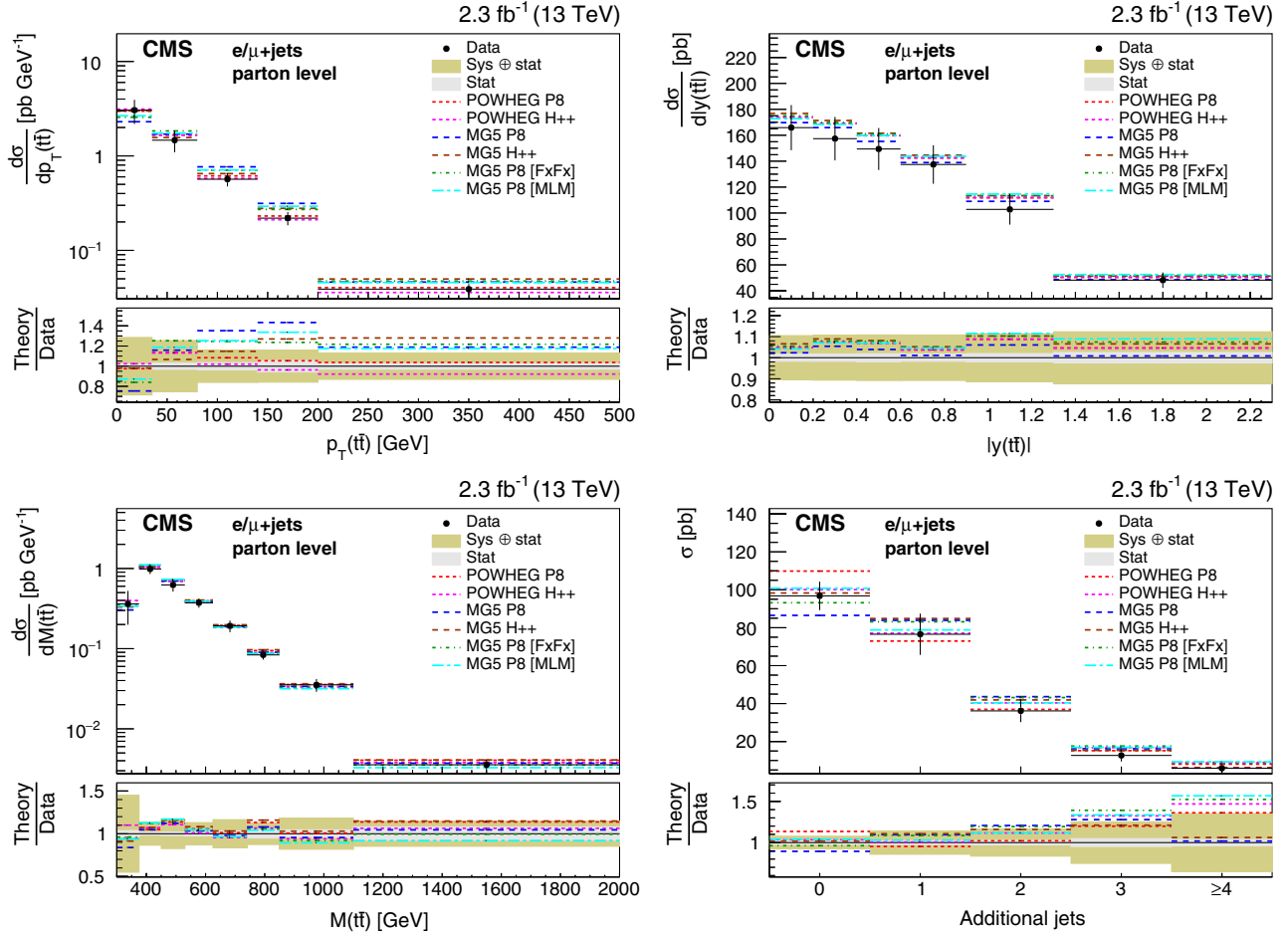


FIG. 9. Differential cross sections at parton level as a function of $p_T(\bar{t}\bar{t})$, $|y(\bar{t}\bar{t})|$, $M(\bar{t}\bar{t})$, and cross sections as a function of the number of additional jets compared to the predictions of POWHEG and MG5_aMC@NLO (MG5) combined with PYTHIA8 (P8) or HERWIG++ (H++) and the multiparton simulations MG5_aMC@NLO +PYTHIA8 MLM and MG5_aMC@NLO +PYTHIA8 FxFx. The ratios of the various predictions to the measured cross sections are shown at the bottom of each panel together with the statistical and systematic uncertainties of the measurement.

For the two-dimensional measurements with n bins in one and m bins in the other quantity the D'Agostini unfolding can be generalized using a vector of $n \cdot m$ entries of the form $b_{1,1}, b_{2,1}, \dots, b_{n,1}, \dots, b_{1,m}, b_{2,m}, \dots, b_{n,m}$ with a corresponding $(n \cdot m) \times (n \cdot m)$ migration matrix. The number of iterations is optimized in the same way.

X. SYSTEMATIC UNCERTAINTIES

We study several sources of experimental and theoretical uncertainty. Uncertainties in the jet and \vec{p}_T^{miss} calibrations, in the pileup modeling, in the b -tagging and lepton selection efficiencies, and in the integrated luminosity measurement fall into the first category.

Uncertainties in the jet energy calibration are estimated by shifting the energies of jets in the simulation up and down by their p_T —and η -dependent uncertainties of 3%–7% [36]. At the same time \vec{p}_T^{miss} is recalculated according to the rescaled jet energies. The recomputed backgrounds, response matrices, and acceptances are used

to unfold the data. The observed differences between these and the original results are taken as an uncertainty in the unfolded event yields. The same technique is used to calculate the impact of the uncertainties in the jet energy resolution, the uncertainty in \vec{p}_T^{miss} not related to the jet energy calibration, in the b -tagging, and in the pileup modeling.

The b -tagging efficiency in the simulation is corrected using scale factors determined from the data [37]. These have an uncertainty of about 2%–5% depending on the p_T of the b jet.

The effect on the measurement due to the uncertainty in the modeling of pileup in the simulation is estimated by varying the average number of pileup events per bunch crossing by 5% and reweighting the simulated events accordingly.

The trigger, reconstruction, and identification efficiencies of leptons are evaluated with tag-and-probe techniques using Z boson dilepton decays [33]. The uncertainties in the scale factors, which are used to correct the simulation to

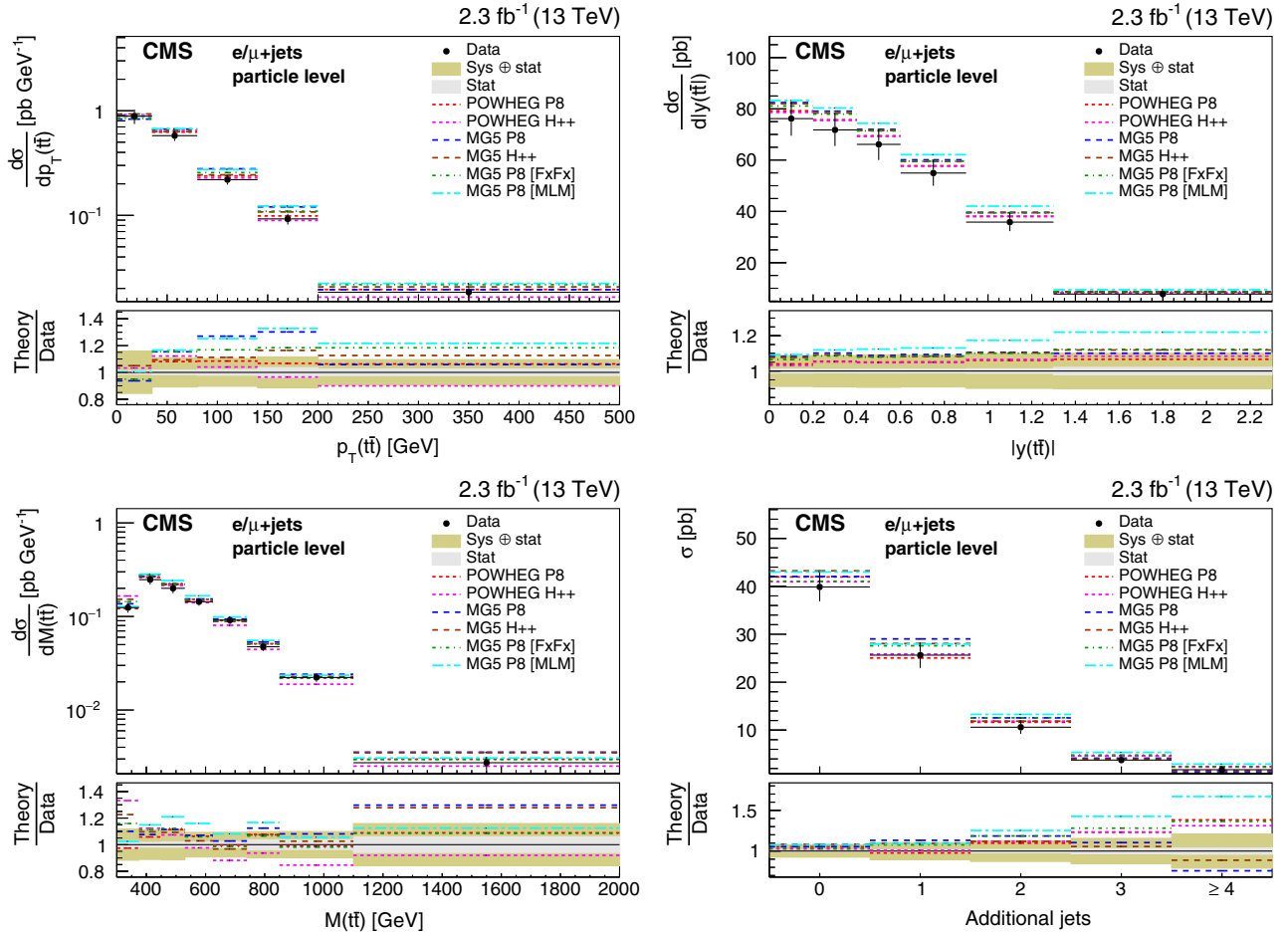


FIG. 10. Differential cross sections at particle level as a function of $p_T(t\bar{t})$, $|y(t\bar{t})|$, $M(t\bar{t})$, and cross sections as a function of the number of additional jets compared to the predictions of POWHEG and MG5_aMC@NLO (MG5) combined with PYTHIA8 (P8) or HERWIG++ (H++) and the multiparton simulations MG5_aMC@NLO + PYTHIA8 MLM and MG5_aMC@NLO + PYTHIA8 FxFx. The ratios of the various predictions to the measured cross sections are shown at the bottom of each panel together with the statistical and systematic uncertainties of the measurement.

match the data, take into account the different lepton selection efficiencies in events with high jet multiplicities. The overall uncertainty in the lepton reconstruction and selection efficiencies is 3%.

The relative uncertainty in the integrated luminosity measurement is 2.3% [1].

Uncertainties in the PDFs, the choice of factorization and renormalization scales, the modeling of the parton shower and hadronization, the effect of different NLO event generation methods, and the top quark mass fall into the second category of theoretical uncertainties.

The effects of these uncertainties are estimated either by using the various event weights introduced in Sec. II, e.g., in the case of PDFs, factorization scale, and renormalization scale, or by using a different $t\bar{t}$ signal simulation. The POWHEG simulation combined with HERWIG++ is used to estimate the effect of different parton shower and hadronization models. In addition, POWHEG+PYTHIA8 samples with a parton shower scale varied by a factor of 2 are used to study the parton shower

modeling uncertainties. The result obtained with MG5_aMC@NLO is used to estimate the effect of different NLO event generation methods. The effect due to uncertainties in the top quark mass is estimated using simulations with altered top quark masses. We quote as uncertainty the cross section differences observed for a top quark mass variation of 1 GeV around the central value of 172.5 GeV used in the central simulation.

The background predictions, response matrices, and acceptances obtained from these simulations are used to unfold the data. The observed deviations with respect to the original result are quoted as an uncertainty in the unfolded event yield.

For the PDF uncertainty only the variation in the acceptance is taken into account while variations due to migrations between bins are neglected. It is calculated according to the uncertainties in the NNPDF30_nlo_as_0118 [19] parametrization. In addition, the uncertainties obtained using the PDF sets derived with varied values of the strong coupling constant $\alpha_s = 0.117$ and 0.119 are considered.

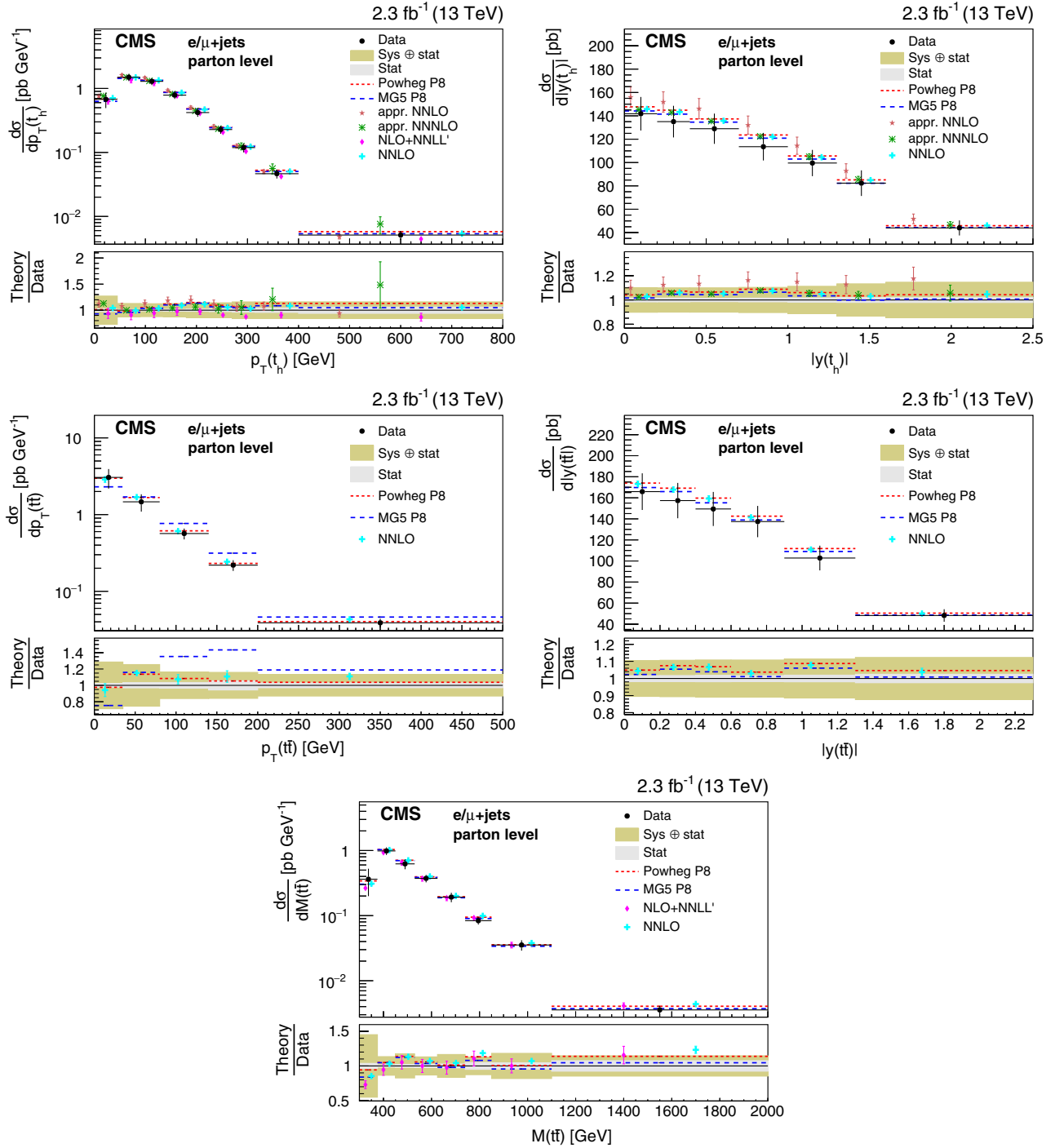


FIG. 11. Differential cross sections at parton level as a function of $p_T(t)$, $|y(t)|$, $p_T(\bar{t})$, $|y(\bar{t})|$, and $M(\bar{t})$ compared to the available predictions of an approximate NNLO calculation [40], an approximate NNNLO calculation [42,43], a NLO + NNLL' calculation [45], and a full NNLO calculation [46]. For these models uncertainties due to the choices of scales are shown. To improve the visibility the theoretical predictions are horizontally shifted. The ratios of the various predictions to the measured cross sections are shown at the bottom of each panel together with the statistical and systematic uncertainties of the measurement.

An overview of the uncertainties in the differential cross sections is provided in Table I, where the typical ranges of uncertainties in the bins are shown. In the double-differential measurements the jet energy scale uncertainty is

about 15% in bins of high jet multiplicities and the dominant uncertainties due to hadronization modeling and NLO calculation reach up to 30% for the parton-level measurements.

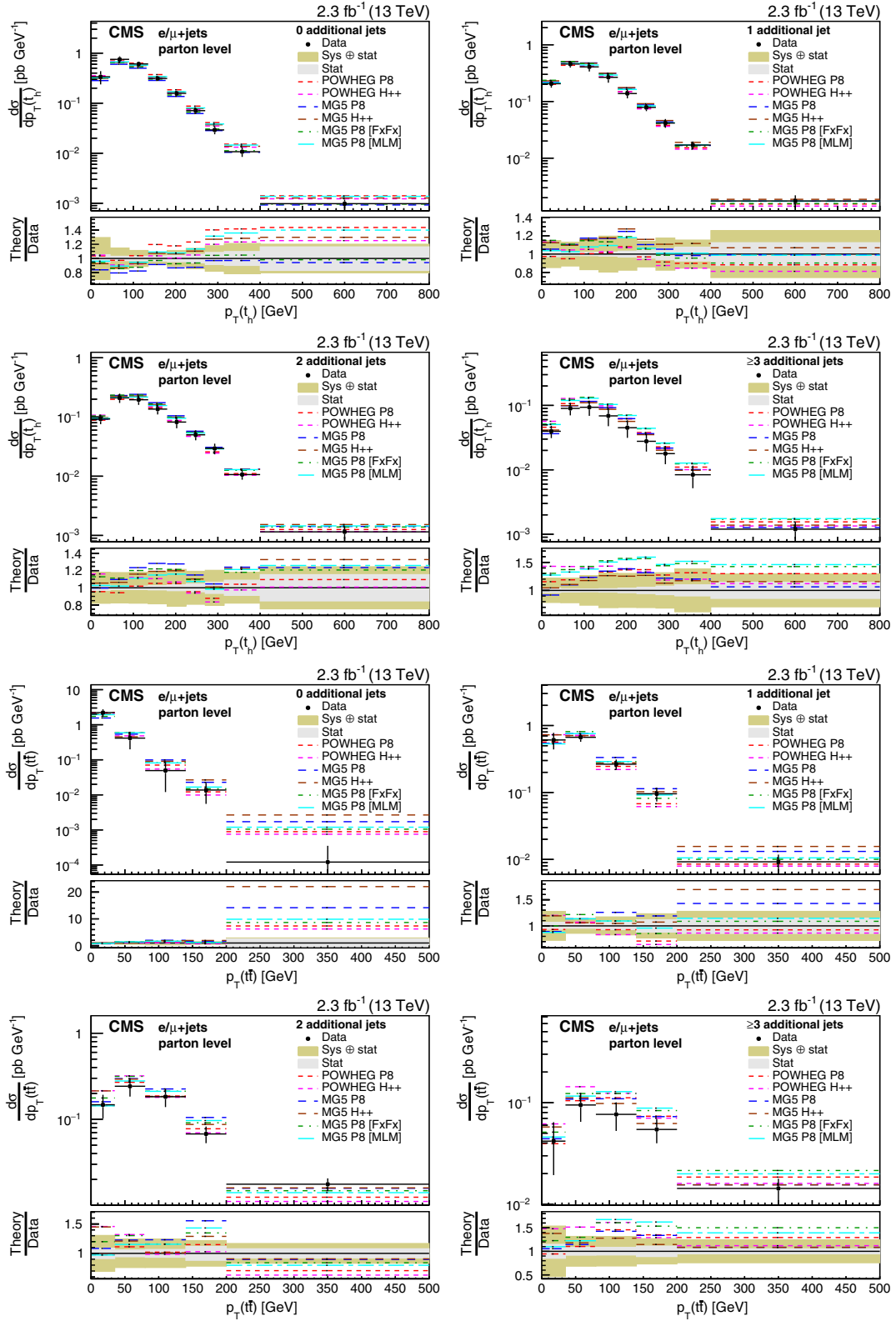


FIG. 12. Differential cross sections at parton level as a function of $p_T(t_h)$ (upper two rows) and $p_T(t_l)$ (lower two rows) in bins of the number of additional jets. The measurements are compared to the predictions of POWHEG and MG5_aMC@NLO (MG5) combined with PYTHIA8 (P8) or HERWIG++ (H++) and the multiparton simulations MG5_aMC@NLO+PYTHIA8 MLM and MG5_aMC@NLO+PYTHIA8 FxFx. The ratios of the predictions to the measured cross sections are shown at the bottom of each panel together with the statistical and systematic uncertainties of the measurement.

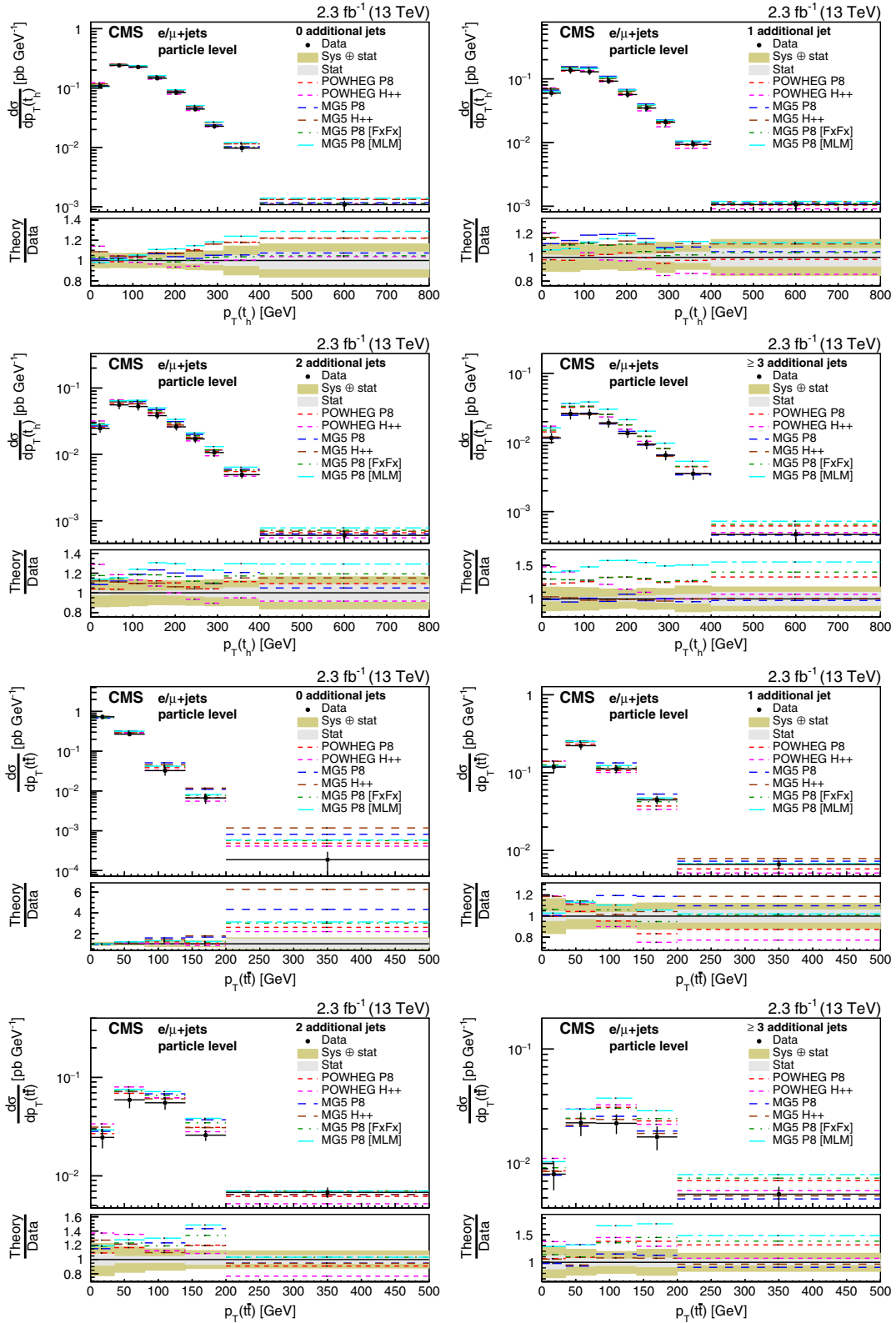


FIG. 13. Differential cross sections at particle level as a function of $p_{T}(t_h)$ (upper two rows) and $p_{T}(t_l)$ (lower two rows) in bins of the number of additional jets. The measurements are compared to the predictions of POWHEG and MG5_aMC@NLO (MG5) combined with PYTHIA8 (P8) or HERWIG++ (H++) and the multiparton simulations MG5_aMC@NLO+PYTHIA8 MLM and MG5_aMC@NLO+PYTHIA8 FxFx. The ratios of the predictions to the measured cross sections are shown at the bottom of each panel together with the statistical and systematic uncertainties of the measurement.

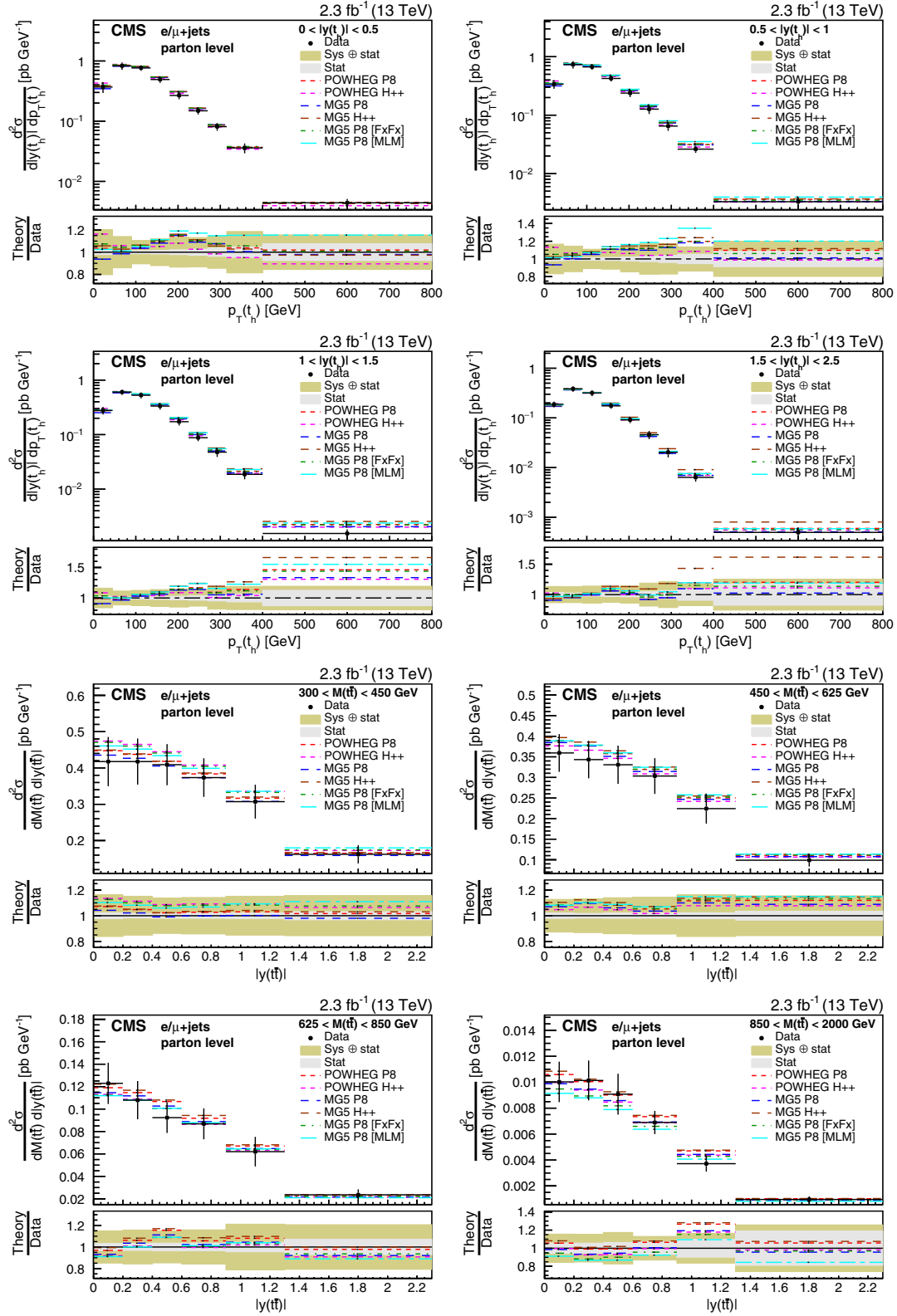


FIG. 14. Double-differential cross sections at parton level as a function of $|y(t_h)|$ vs $p_T(t_h)$ (upper two rows) and $M(t\bar{t})$ vs $|y(t\bar{t})|$ (lower two rows). The measurements are compared to the predictions of POWHEG and MG5_aMC@NLO (MG5) combined with PYTHIA8 (P8) or HERWIG++ (H++) and the multiparton simulations MG5_aMC@NLO +PYTHIA8 MLM and MG5_aMC@NLO +PYTHIA8 FxFx. The ratios of the predictions to the measured cross sections are shown at the bottom of each panel together with the statistical and systematic uncertainties of the measurement.

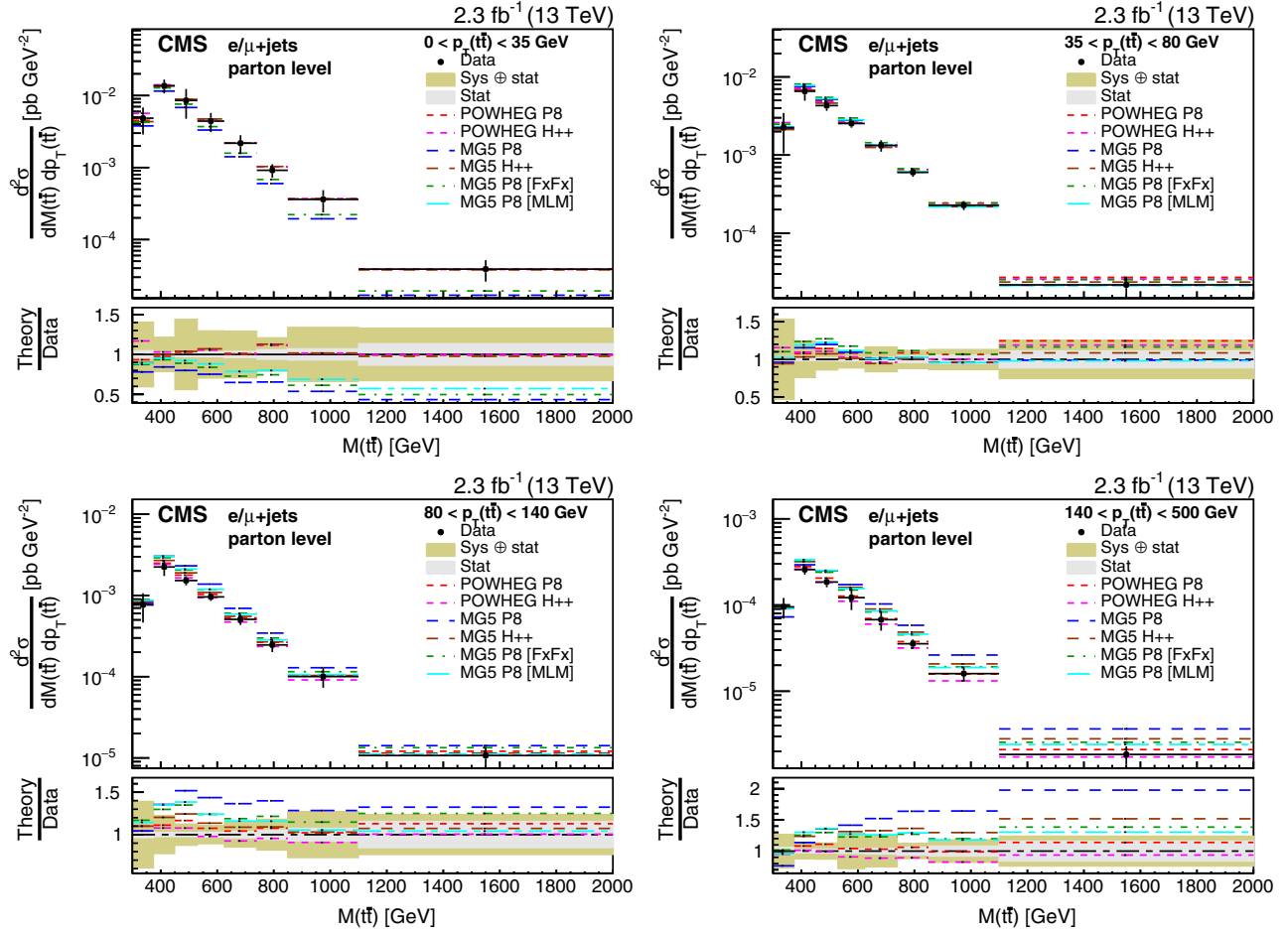


FIG. 15. Double-differential cross section at parton level as a function of $p_T(\bar{t}\bar{\tau})$ vs $M(\bar{t}\bar{\tau})$. The measurements are compared to the predictions of POWHEG and MG5_aMC@NLO (MG5) combined with PYTHIA8 (P8) or HERWIG++ (H++) and the multiparton simulations MG5_aMC@NLO+PYTHIA8 MLM and MG5_aMC@NLO+PYTHIA8 FxFx. The ratios of the predictions to the measured cross sections are shown at the bottom of each panel together with the statistical and systematic uncertainties of the measurement.

XI. CROSS SECTION RESULTS

The cross section σ in each bin is calculated as the ratio of the unfolded signal yield and the integrated luminosity. These are further divided by the bin width (the product of the two bin widths) to obtain the single- (double-) differential results.

The measured differential cross sections are compared to the predictions of POWHEG and MG5_aMC@NLO, each combined with the parton shower simulations of PYTHIA8 and HERWIG++. In addition, the $\bar{t}\bar{\tau}$ multiparton simulations of MG5_aMC@NLO at LO and NLO with a PYTHIA8 parton shower are shown in Fig. 7 (8) as a function of the top quark p_T and $|y|$ at parton (particle) level. In Figs. 9 and 10 the cross sections as a function of kinematic variables of the $\bar{t}\bar{\tau}$ system and the number of additional jets are compared to the same theoretical predictions.

In Fig. 11 the parton-level results are compared to theoretical predictions of various accuracies. The first is an approximate NNLO [40] QCD calculation using the

CT14NNLO [41] PDF and $m_t = 172.5$ GeV. The factorization and renormalization scales are fixed at m_t . The second is an approximate next-to-NNLO (NNNLO) [42,43] QCD calculation using the MSTW2008nnlo [44] PDF, $m_t = 172.5$ GeV and factorization and renormalization scales fixed at m_t . The third combines the NLO QCD calculation with an improved NNLL QCD calculation (NLO + NNLL') [45] using the MSTW2008nnlo PDF, $m_t = 173.2$ GeV, and the renormalization and factorization scales of $M_T = \sqrt{m_t^2 + p_T^2(t)}$ for the $p_T(t)$ calculation and $M(\bar{t}\bar{\tau})/2$ for the $M(\bar{t}\bar{\tau})$ calculation. The fourth is a full NNLO [46] QCD calculation using the NNPDF3.0 PDF, $m_t = 173.3$ GeV, and the renormalization and factorization scales of $M_T/2$ for the $p_T(t)$ calculation and one fourth of the sum of the p_T of all partons for the other distributions. The displayed uncertainties come from varying the scales up and down by a factor of 2. Only the uncertainties in the approximate NNLO calculation include PDF uncertainties and a m_t variation of 1 GeV.

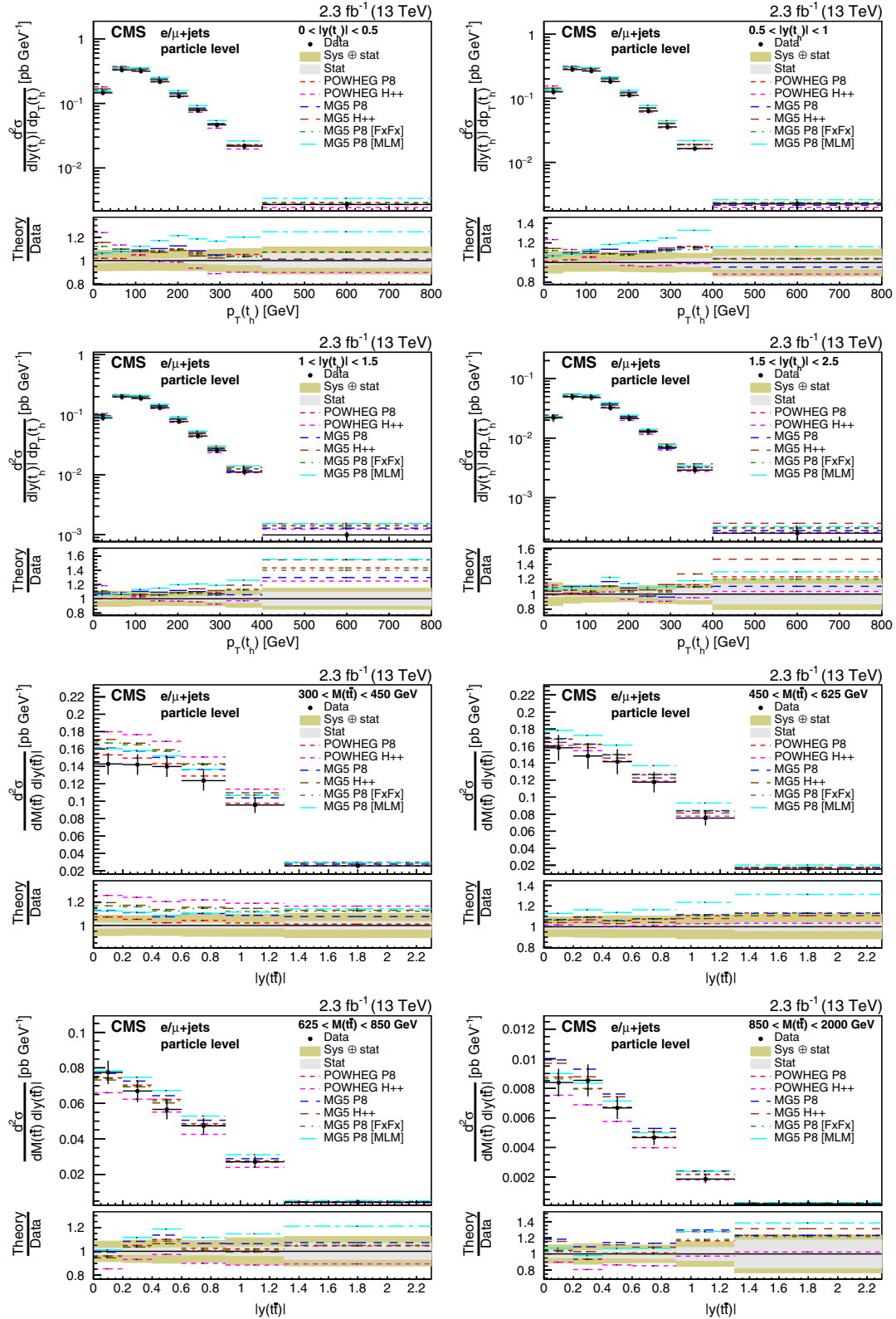


FIG. 16. Double-differential cross sections at particle level as a function of $|y(t_h)|$ vs $p_T(t_h)$ (upper two rows) and $M(t\bar{t})$ vs $|y(t\bar{t})|$ (lower two rows). The measurements are compared to the predictions of POWHEG and MG5_aMC@NLO (MG5) combined with PYTHIA8 (P8) or HERWIG++ (H++) and the multiparton simulations MG5_aMC@NLO+PYTHIA8 MLM and MG5_aMC@NLO+PYTHIA8 FxFx. The ratios of the predictions to the measured cross sections are shown at the bottom of each panel together with the statistical and systematic uncertainties of the measurement.

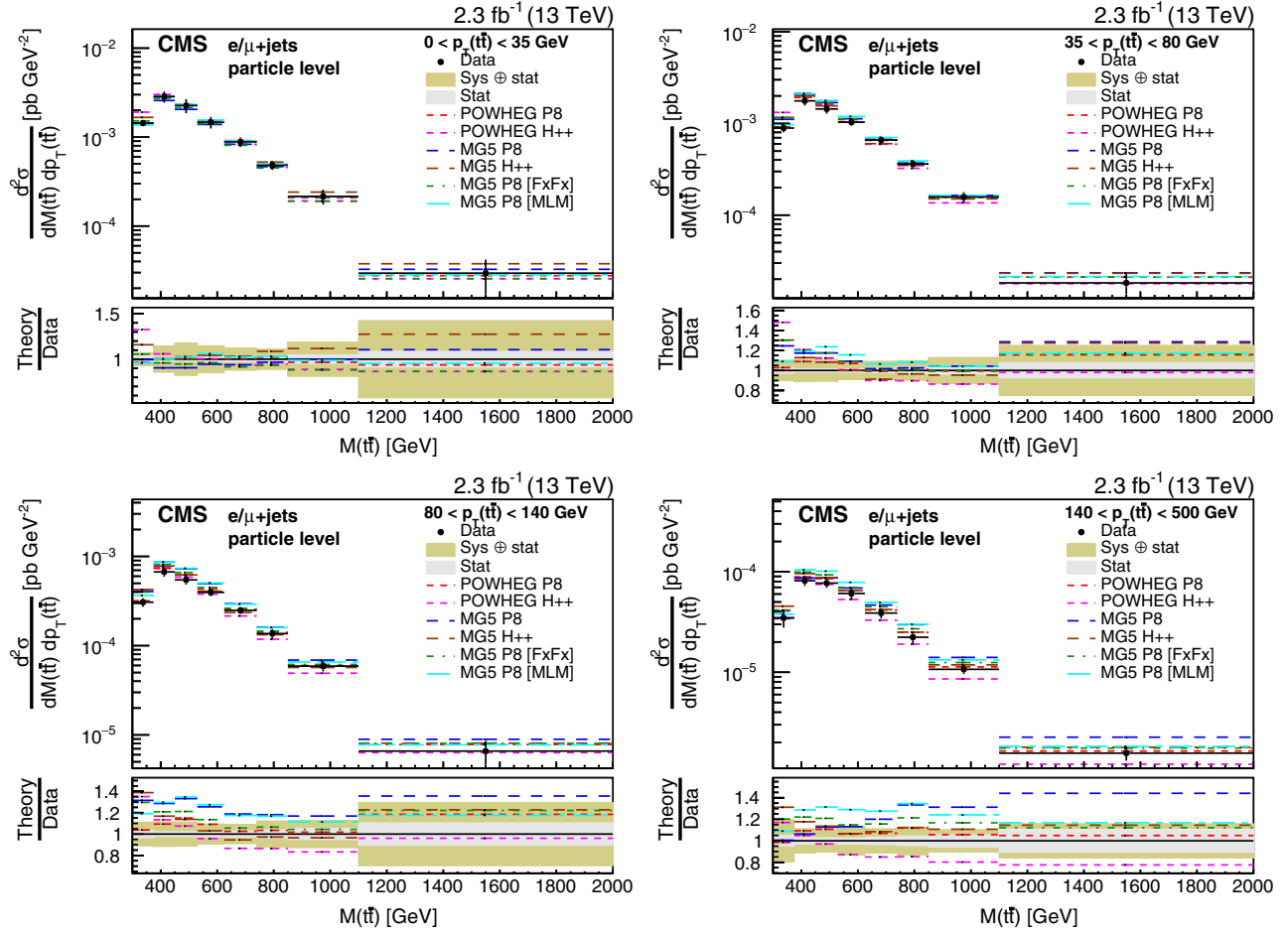


FIG. 17. Double-differential cross section at particle level as a function of $p_T(t\bar{t})$ vs $M(t\bar{t})$. The measurements are compared to the predictions of POWHEG and MG5_aMC@NLO (MG5) combined with PYTHIA8 (P8) or HERWIG++ (H++) and the multiparton simulations MG5_aMC@NLO +PYTHIA8 MLM and MG5_aMC@NLO +PYTHIA8 FxFx. The ratios of the predictions to the measured cross sections are shown at the bottom of each panel together with the statistical and systematic uncertainties of the measurement.

The differential cross sections as a function of $p_T(t_h)$ and $p_T(t\bar{t})$ in bins of the number of additional jets are shown in Fig. 12 (13) at parton (particle) level. The double-differential cross sections as a function of $|y(t_h)|$ vs $p_T(t_h)$, $M(t\bar{t})$ vs $|y(t\bar{t})|$, and $p_T(t\bar{t})$ vs $M(t\bar{t})$ are shown at parton level in Figs. 14 and 15 and at particle level in Figs. 16 and 17. The results are compared to the predictions of the event generators. All cross section values together with their statistical and systematic uncertainties are listed in Appendixes A, Tables IV–XVI, and B, Tables XVII–XXIX, for the parton- and particle-level measurements, respectively.

The precision of the measurement is limited by systematic uncertainties, dominated by jet energy scale uncertainties on the experimental side and parton shower and hadronization modeling uncertainties on the theoretical side. As expected, the theoretical uncertainties are reduced in the particle-level measurements since these are less dependent on theory-based extrapolations.

We evaluate the level of agreement between the measured differential cross sections and the various theoretical

predictions using χ^2 tests. In these tests we take into account the full covariance matrix obtained from the unfolding procedure for the statistical uncertainty. For each of the studied systematic uncertainties we assume a full correlation among all bins. No uncertainties in the theoretical predictions are considered for this comparison. However, these uncertainties are known to be large. Typically, differences between the various models are used to assess their uncertainties. From the χ^2 values and the numbers of degrees of freedom, which corresponds to the number of bins in the distributions, the p-values are calculated. The results are shown in Table II for the parton-level and in Table III for the particle-level measurements.

The observed cross sections are slightly lower than expected. However, taking into account the systematic uncertainties that are highly correlated among the bins, there is no significant deviation. In general, the measured distributions are in agreement with the predictions of the event generators with some exceptions in the $p_T(t\bar{t})$ and $M(t\bar{t})$ distributions. The jet multiplicities are lower than predicted by

TABLE II. Comparison between the measured distributions at parton level and the predictions of POWHEG and MG5_aMC@NLO combined with PYTHIA8 (P8) or HERWIG++ (H++) and the multiparton simulations MG5_aMC@NLO MLM and MG5_aMC@NLO FxFx, as well as the predictions of an approximate NNNLO calculation [42,43], a NLO + NNLL' calculation [45], and a full NNLO calculation [46]. We list the results of the χ^2 tests together with the numbers of degrees of freedom (d.o.f.) and the corresponding p-values. For the comparison no uncertainties in the theoretical predictions are taken into account.

Distribution	$\chi^2/\text{d.o.f.}$	p-value	$\chi^2/\text{d.o.f.}$	p-value	$\chi^2/\text{d.o.f.}$	p-value
POWHEG+P8						
Order: NLO						
$p_T(t_h)$	10.7/9	0.295	8.01/9	0.533	19.0/9	0.025
$|y(t_h)|$	3.91/7	0.790	4.33/7	0.741	4.49/7	0.721
$p_T(t_\ell)$	14.9/9	0.093	9.03/9	0.435	41.8/9	<0.01
$|y(t_\ell)|$	11.4/7	0.121	13.1/7	0.070	12.0/7	0.100
$M(t\bar{t})$	5.61/8	0.691	10.9/8	0.206	45.0/8	<0.01
$p_T(t\bar{t})$	0.941/5	0.967	4.34/5	0.501	16.8/5	<0.01
$|y(t\bar{t})|$	1.95/6	0.924	2.04/6	0.916	5.55/6	0.476
Additional jets	8.22/5	0.145	6.88/5	0.230	5.82/5	0.324
Additional jets vs $p_T(t\bar{t})$	85.3/20	<0.01	132/20	<0.01	135/20	<0.01
Additional jets vs $p_T(t_h)$	89.0/36	<0.01	43.1/36	0.193	71.7/36	<0.01
$|y(t_h)|$ vs $p_T(t_h)$	55.3/36	0.021	52.4/36	0.038	60.7/36	<0.01
$M(t\bar{t})$ vs $|y(t\bar{t})|$	19.3/24	0.734	18.3/24	0.788	49.4/24	<0.01
$p_T(t\bar{t})$ vs $M(t\bar{t})$	14.5/32	0.997	26.2/32	0.755	100/32	<0.01
MG5_aMC@NLO+P8						
Order: NLO						
$p_T(t_h)$	8.68/9	0.467	15.3/9	0.084	9.35/9	0.406
$|y(t_h)|$	4.11/7	0.767	5.42/7	0.608	3.91/7	0.790
$p_T(t_\ell)$	13.0/9	0.162	26.8/9	<0.01	11.7/9	0.228
$|y(t_\ell)|$	14.3/7	0.046	10.7/7	0.151	16.4/7	0.022
$M(t\bar{t})$	9.91/8	0.271	5.93/8	0.655	28.0/8	<0.01
$p_T(t\bar{t})$	31.1/5	<0.01	24.6/5	<0.01	18.4/5	<0.01
$|y(t\bar{t})|$	1.97/6	0.923	2.04/6	0.916	2.49/6	0.870
Additional jets	21.5/5	<0.01	4.21/5	0.520	7.98/5	0.158
Additional jets vs $p_T(t\bar{t})$	319/20	<0.01	259/20	<0.01	121/20	<0.01
Additional jets vs $p_T(t_h)$	90.9/36	<0.01	45.0/36	0.145	52.5/36	0.037
$|y(t_h)|$ vs $p_T(t_h)$	73.1/36	<0.01	111/36	<0.01	48.1/36	0.086
$M(t\bar{t})$ vs $|y(t\bar{t})|$	26.1/24	0.347	17.8/24	0.811	36.7/24	0.047
$p_T(t\bar{t})$ vs $M(t\bar{t})$	229/32	<0.01	71.5/32	<0.01	97.6/32	<0.01
MG5_aMC@NLO+H++						
Order: NLO						
$p_T(t_h)$	8.68/9	0.467	15.3/9	0.084	9.35/9	0.406
$|y(t_h)|$	4.11/7	0.767	5.42/7	0.608	3.91/7	0.790
$p_T(t_\ell)$	13.0/9	0.162	26.8/9	<0.01	11.7/9	0.228
$ y(t_\ell) $	14.3/7	0.046	10.7/7	0.151	16.4/7	0.022
$M(t\bar{t})$	9.91/8	0.271	5.93/8	0.655	28.0/8	<0.01
$p_T(t\bar{t})$	31.1/5	<0.01	24.6/5	<0.01	18.4/5	<0.01
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Additional jets vs $p_T(t\bar{t})$	319/20	<0.01	259/20	<0.01	121/20	<0.01
Additional jets vs $p_T(t_h)$	90.9/36	<0.01	45.0/36	0.145	52.5/36	0.037
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$M(t\bar{t})$ vs $ y(t\bar{t}) $	26.1/24	0.347	17.8/24	0.811	36.7/24	0.047
$p_T(t\bar{t})$ vs $M(t\bar{t})$	229/32	<0.01	71.5/32	<0.01	97.6/32	<0.01
MG5_aMC@NLO+P8 FxFx						
Order: NLO, up to two add. partons						
$p_T(t_h)$	8.68/9	0.467	15.3/9	0.084	9.35/9	0.406
$|y(t_h)|$	4.11/7	0.767	5.42/7	0.608	3.91/7	0.790
$p_T(t_\ell)$	13.0/9	0.162	26.8/9	<0.01	11.7/9	0.228
$|y(t_\ell)|$	14.3/7	0.046	10.7/7	0.151	16.4/7	0.022
$M(t\bar{t})$	9.91/8	0.271	5.93/8	0.655	28.0/8	<0.01
$p_T(t\bar{t})$	31.1/5	<0.01	24.6/5	<0.01	18.4/5	<0.01
$|y(t\bar{t})|$	1.97/6	0.923	2.04/6	0.916	2.49/6	0.870
Additional jets	21.5/5	<0.01	4.21/5	0.520	7.98/5	0.158
Additional jets vs $p_T(t\bar{t})$	319/20	<0.01	259/20	<0.01	121/20	<0.01
Additional jets vs $p_T(t_h)$	90.9/36	<0.01	45.0/36	0.145	52.5/36	0.037
$|y(t_h)|$ vs $p_T(t_h)$	73.1/36	<0.01	111/36	<0.01	48.1/36	0.086
$M(t\bar{t})$ vs $|y(t\bar{t})|$	26.1/24	0.347	17.8/24	0.811	36.7/24	0.047
$p_T(t\bar{t})$ vs $M(t\bar{t})$	229/32	<0.01	71.5/32	<0.01	97.6/32	<0.01
appr. NNLO						
$p_T(t_h)$	14.3/9	0.111	36.7/9	<0.01	6.29/9	0.710
$|y(t_h)|$	5.30/7	0.623	2.59/7	0.920	...	...
$p_T(t_\ell)$	12.1/9	0.209	92.1/9	<0.01	3.06/9	0.962
$|y(t_\ell)|$	3.77/7	0.805	4.34/7	0.739	...	...
$M(t\bar{t})$	...	...	...	...	6.70/8	0.569
NNLO						
$p_T(t_h)$	5.78/9	0.762				
$|y(t_h)|$	2.20/7	0.948				
$p_T(t_\ell)$	5.54/9	0.785				
$|y(t_\ell)|$	6.48/7	0.485				
$M(t\bar{t})$	5.88/8	0.660				
$p_T(t\bar{t})$	3.50/5	0.623				
$|y(t\bar{t})|$	1.42/6	0.965				

almost all simulations. The measured p_T of the top quarks is slightly softer than predicted. Such an effect has already been observed in previous measurements [2–5]. However, the comparison between the HERWIG++ and PYTHIA8 simulations together with the same matrix-element calculations shows

the large impact of the parton shower and hadronization modeling. The parton-level results are well described by the matrix-element calculations. Especially, the soft p_T of the top quarks is predicted by the NNLO and NLO + NNLL' QCD calculation.

TABLE III. Comparison between the measured distributions at particle level and the predictions of POWHEG and MG5_aMC@NLO combined with PYTHIA8 (P8) or HERWIG++ (H++) and the multiparton simulations MG5_aMC@NLO MLM and MG5_aMC@NLO FxFx. We list the results of the χ^2 tests together with the numbers of d.o.f. and the corresponding p-values. For the comparison no uncertainties in the theoretical predictions are taken into account.

Distribution	χ^2 /d.o.f.	p-value	χ^2 /d.o.f.	p-value	χ^2 /d.o.f.	p-value
POWHEG+P8						
Order: NLO						
$p_T(t_h)$	14.2/9	0.115	24.0/9	<0.01	32.8/9	<0.01
$|y(t_h)|$	3.47/7	0.838	5.66/7	0.579	6.64/7	0.468
$p_T(t_\ell)$	20.8/9	0.013	38.2/9	<0.01	49.7/9	<0.01
$|y(t_\ell)|$	6.37/7	0.497	9.69/7	0.207	16.1/7	0.025
$M(t\bar{t})$	9.03/8	0.340	148/8	<0.01	12.0/8	0.151
$p_T(t\bar{t})$	2.15/5	0.829	29.4/5	<0.01	49.2/5	<0.01
$|y(t\bar{t})|$	0.869/6	0.990	2.06/6	0.914	13.2/6	0.040
Additional jets	28.2/5	<0.01	17.2/5	<0.01	36.8/5	<0.01
Additional jets vs $p_T(t\bar{t})$	70.7/20	<0.01	86.1/20	<0.01	161/20	<0.01
Additional jets vs $p_T(t_h)$	91.6/36	<0.01	200/36	<0.01	162/36	<0.01
$|y(t_h)|$ vs $p_T(t_h)$	56.2/36	0.017	197/36	<0.01	114/36	<0.01
$M(t\bar{t})$ vs $|y(t\bar{t})|$	26.6/24	0.324	263/24	<0.01	38.1/24	0.034
$p_T(t\bar{t})$ vs $M(t\bar{t})$	13.4/32	0.998	459/32	<0.01	89.0/32	<0.01
MG5_aMC@NLO+P8						
Order: NLO						
$p_T(t_h)$	11.9/9	0.221	5.51/9	0.788	4.17/9	0.900
$|y(t_h)|$	7.34/7	0.394	10.6/7	0.156	5.93/7	0.547
$p_T(t_\ell)$	11.0/9	0.274	6.37/9	0.702	6.51/9	0.688
$|y(t_\ell)|$	12.3/7	0.092	6.04/7	0.535	14.3/7	0.047
$M(t\bar{t})$	9.57/8	0.296	28.7/8	<0.01	28.5/8	<0.01
$p_T(t\bar{t})$	37.1/5	<0.01	7.92/5	0.161	29.6/5	<0.01
$|y(t\bar{t})|$	1.75/6	0.942	1.98/6	0.922	2.87/6	0.825
Additional jets	29.6/5	<0.01	12.2/5	0.032	11.6/5	0.041
Additional jets vs $p_T(t\bar{t})$	197/20	<0.01	163/20	<0.01	85.3/20	<0.01
Additional jets vs $p_T(t_h)$	151/36	<0.01	57.7/36	0.012	40.4/36	0.282
$|y(t_h)|$ vs $p_T(t_h)$	36.6/36	0.441	82.5/36	<0.01	42.2/36	0.222
$M(t\bar{t})$ vs $|y(t\bar{t})|$	21.4/24	0.612	47.9/24	<0.01	52.3/24	<0.01
$p_T(t\bar{t})$ vs $M(t\bar{t})$	119/32	<0.01	164/32	<0.01	107/32	<0.01
MG5_aMC@NLO+H++						
Order: NLO						
$p_T(t_h)$	11.9/9	0.221	5.51/9	0.788	4.17/9	0.900
$|y(t_h)|$	7.34/7	0.394	10.6/7	0.156	5.93/7	0.547
$p_T(t_\ell)$	11.0/9	0.274	6.37/9	0.702	6.51/9	0.688
$|y(t_\ell)|$	12.3/7	0.092	6.04/7	0.535	14.3/7	0.047
$M(t\bar{t})$	9.57/8	0.296	28.7/8	<0.01	28.5/8	<0.01
$p_T(t\bar{t})$	37.1/5	<0.01	7.92/5	0.161	29.6/5	<0.01
$|y(t\bar{t})|$	1.75/6	0.942	1.98/6	0.922	2.87/6	0.825
Additional jets	29.6/5	<0.01	12.2/5	0.032	11.6/5	0.041
Additional jets vs $p_T(t\bar{t})$	197/20	<0.01	163/20	<0.01	85.3/20	<0.01
Additional jets vs $p_T(t_h)$	151/36	<0.01	57.7/36	0.012	40.4/36	0.282
$|y(t_h)|$ vs $p_T(t_h)$	36.6/36	0.441	82.5/36	<0.01	42.2/36	0.222
$M(t\bar{t})$ vs $|y(t\bar{t})|$	21.4/24	0.612	47.9/24	<0.01	52.3/24	<0.01
$p_T(t\bar{t})$ vs $M(t\bar{t})$	119/32	<0.01	164/32	<0.01	107/32	<0.01
MG5_aMC@NLO+P8 FxFx						
Order: NLO, up to two add. partons						
$p_T(t_h)$	11.9/9	0.221	5.51/9	0.788	4.17/9	0.900
$|y(t_h)|$	7.34/7	0.394	10.6/7	0.156	5.93/7	0.547
$p_T(t_\ell)$	11.0/9	0.274	6.37/9	0.702	6.51/9	0.688
$|y(t_\ell)|$	12.3/7	0.092	6.04/7	0.535	14.3/7	0.047
$M(t\bar{t})$	9.57/8	0.296	28.7/8	<0.01	28.5/8	<0.01
$p_T(t\bar{t})$	37.1/5	<0.01	7.92/5	0.161	29.6/5	<0.01
$|y(t\bar{t})|$	1.75/6	0.942	1.98/6	0.922	2.87/6	0.825
Additional jets	29.6/5	<0.01	12.2/5	0.032	11.6/5	0.041
Additional jets vs $p_T(t\bar{t})$	197/20	<0.01	163/20	<0.01	85.3/20	<0.01
Additional jets vs $p_T(t_h)$	151/36	<0.01	57.7/36	0.012	40.4/36	0.282
$|y(t_h)|$ vs $p_T(t_h)$	36.6/36	0.441	82.5/36	<0.01	42.2/36	0.222
$M(t\bar{t})$ vs $|y(t\bar{t})|$	21.4/24	0.612	47.9/24	<0.01	52.3/24	<0.01
$p_T(t\bar{t})$ vs $M(t\bar{t})$	119/32	<0.01	164/32	<0.01	107/32	<0.01

XII. SUMMARY

Measurements of the differential and double-differential cross sections for $t\bar{t}$ production in proton-proton collisions at 13 TeV have been presented. The data correspond to an integrated luminosity of 2.3 fb^{-1} recorded by the CMS experiment. The $t\bar{t}$ production cross section is measured in the lepton + jets channel as a function of transverse momentum p_T and rapidity $|y|$ of the top quarks; p_T , $|y|$, and invariant mass of the $t\bar{t}$ system; and the number of additional jets. The measurement at parton level is dominated by the uncertainties in the parton shower and hadronization modeling. The dependence on these theoretical models is reduced for the particle-level measurement, for which the experimental uncertainties of jet energy calibration and b -tagging efficiency are dominant.

The results are compared to several standard model predictions that use different methods and approximations for their calculations. In general, the measured cross sections are slightly lower than predicted, but within the

uncertainty compatible with the expectation. The measured distributions are in agreement with the predictions of the event generators with some exceptions in the $p_T(t\bar{t})$ and $M(t\bar{t})$ distributions. The number of additional jets is lower and the measured p_T of the top quarks is slightly softer than predicted by most of the event generators. A softer p_T of the top quarks has already been observed in previous measurements and is predicted by the NNLO and the NLO + NNLL' QCD calculation.

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APPENDIX A: TABLES OF PARTON-LEVEL CROSS SECTIONS

TABLE IV. Differential cross section at parton level as a function of $p_T(t_h)$. The values are shown together with their statistical and systematic uncertainties.

$p_T(t_h)$ [GeV]	$\frac{d\sigma}{dp_T(t_h)}$ [fb GeV ⁻¹]	$p_T(t_h)$ [GeV]	$\frac{d\sigma}{dp_T(t_h)}$ [fb GeV ⁻¹]
0–45	$680 \pm 20 \pm 180$	225–270	$228 \pm 6 \pm 32$
45–90	$1500 \pm 20 \pm 190$	270–315	$119 \pm 5 \pm 18$
90–135	$1290 \pm 20 \pm 160$	315–400	$46 \pm 2 \pm 7$
135–180	$790 \pm 10 \pm 100$	400–800	$5.1 \pm 0.3 \pm 0.8$
180–225	$420 \pm 9 \pm 59$		

TABLE V. Differential cross section at parton level as a function of $|y(t_h)|$. The values are shown together with their statistical and systematic uncertainties.

$|y(t_h)|$	$\frac{d\sigma}{d|y(t_h)|}$ [pb]	$|y(t_h)|$	$\frac{d\sigma}{d|y(t_h)|}$ [pb]
0–0.2	$142 \pm 2 \pm 14$	1–1.3	$100 \pm 2 \pm 11$
0.2–0.4	$135 \pm 2 \pm 13$	1.3–1.6	$82 \pm 2 \pm 11$
0.4–0.7	$129 \pm 2 \pm 13$	1.6–2.5	$44.0 \pm 0.9 \pm 6.4$
0.7–1	$114 \pm 2 \pm 12$		

TABLE VI. Differential cross section at parton level as a function of $p_T(t_\ell)$. The values are shown together with their statistical and systematic uncertainties.

$p_T(t_\ell)$ [GeV]	$\frac{d\sigma}{dp_T(t_\ell)}$ [fb GeV ⁻¹]	$p_T(t_\ell)$ [GeV]	$\frac{d\sigma}{dp_T(t_\ell)}$ [fb GeV ⁻¹]
0–45	$690 \pm 10 \pm 100$	225–270	$218 \pm 4 \pm 20$
45–90	$1470 \pm 20 \pm 190$	270–315	$115 \pm 3 \pm 14$
90–135	$1300 \pm 10 \pm 150$	315–400	$47 \pm 1 \pm 6$
135–180	$810 \pm 10 \pm 91$	400–800	$4.8 \pm 0.2 \pm 0.5$
180–225	$432 \pm 7 \pm 44$		

TABLE VII. Differential cross section at parton level as a function of $|y(t_\ell)|$. The values are shown together with their statistical and systematic uncertainties.

$|y(t_\ell)|$	$\frac{d\sigma}{d|y(t_\ell)|}$ [pb]	$|y(t_\ell)|$	$\frac{d\sigma}{d|y(t_\ell)|}$ [pb]
0–0.2	$135 \pm 2 \pm 14$	1–1.3	$101 \pm 1 \pm 11$
0.2–0.4	$133 \pm 1 \pm 14$	1.3–1.6	$82 \pm 1 \pm 9$
0.4–0.7	$128 \pm 1 \pm 14$	1.6–2.5	$45.5 \pm 0.9 \pm 5.1$
0.7–1	$118 \pm 1 \pm 13$		

TABLE VIII. Differential cross section at parton level as a function of $p_T(\tilde{t}\tilde{t})$. The values are shown together with their statistical and systematic uncertainties.

$p_T(\tilde{t}\tilde{t})$ [GeV]	$\frac{d\sigma}{dp_T(\tilde{t}\tilde{t})}$ [fb GeV ⁻¹]	$p_T(\tilde{t}\tilde{t})$ [GeV]	$\frac{d\sigma}{dp_T(\tilde{t}\tilde{t})}$ [fb GeV ⁻¹]
0–35	$3050 \pm 70 \pm 870$	140–200	$220 \pm 10 \pm 30$
35–80	$1470 \pm 50 \pm 370$	200–500	$39 \pm 1 \pm 5$
80–140	$570 \pm 20 \pm 90$		

TABLE IX. Differential cross section at parton level as a function of $M(\tilde{t}\tilde{t})$. The values are shown together with their statistical and systematic uncertainties.

$M(\tilde{t}\tilde{t})$ [GeV]	$\frac{d\sigma}{dM(\tilde{t}\tilde{t})}$ [fb GeV ⁻¹]	$M(\tilde{t}\tilde{t})$ [GeV]	$\frac{d\sigma}{dM(\tilde{t}\tilde{t})}$ [fb GeV ⁻¹]
300–375	$360 \pm 10 \pm 160$	625–740	$192 \pm 6 \pm 31$
375–450	$990 \pm 20 \pm 130$	740–850	$84 \pm 4 \pm 10$
450–530	$620 \pm 10 \pm 110$	850–1100	$35 \pm 2 \pm 6$
530–625	$373 \pm 9 \pm 48$	1100–2000	$3.6 \pm 0.3 \pm 0.4$

TABLE X. Differential cross section at parton level as a function of $|y(\tilde{t}\tilde{t})|$. The values are shown together with their statistical and systematic uncertainties.

$|y(\tilde{t}\tilde{t})|$	$\frac{d\sigma}{d|y(\tilde{t}\tilde{t})|}$ [pb]	$|y(\tilde{t}\tilde{t})|$	$\frac{d\sigma}{d|y(\tilde{t}\tilde{t})|}$ [pb]
0–0.2	$166 \pm 3 \pm 17$	0.6–0.9	$137 \pm 2 \pm 15$
0.2–0.4	$157 \pm 3 \pm 17$	0.9–1.3	$103 \pm 2 \pm 12$
0.4–0.6	$149 \pm 3 \pm 16$	1.3–2.3	$48 \pm 1 \pm 6$

TABLE XI. Cross sections at parton level in bins of the number of additional jets. The values are shown together with their statistical and systematic uncertainties.

Additional jets	σ [pb]	Additional jets	σ [pb]
0	$97 \pm 2 \pm 7$	3	$12.7 \pm 0.6 \pm 3.1$
1	$77 \pm 2 \pm 11$	≥ 4	$5.9 \pm 0.2 \pm 2.1$
2	$36 \pm 1 \pm 6$		

TABLE XII. Differential cross sections at parton level as a function of $p_T(t_h)$ in bins of the number of additional jets. The values are shown together with their statistical and systematic uncertainties.

$p_T(t_h)$ [GeV]	$\frac{d\sigma}{dp_T(t_h)}$ [fb GeV ⁻¹]	$p_T(t_h)$ [GeV]	$\frac{d\sigma}{dp_T(t_h)}$ [fb GeV ⁻¹]
Additional jets: 0			
0–45	$340 \pm 20 \pm 100$	225–270	$71 \pm 4 \pm 9$
45–90	$750 \pm 20 \pm 110$	270–315	$29 \pm 3 \pm 5$
90–135	$610 \pm 20 \pm 70$	315–400	$11 \pm 1 \pm 2$
135–180	$310 \pm 10 \pm 20$	400–800	$1.0 \pm 0.2 \pm 0.1$
180–225	$157 \pm 7 \pm 16$		
Additional jets: 1			
0–45	$206 \pm 6 \pm 30$	225–270	$79 \pm 4 \pm 11$
45–90	$458 \pm 9 \pm 60$	270–315	$42 \pm 3 \pm 7$
90–135	$408 \pm 8 \pm 69$	315–400	$17 \pm 1 \pm 2$
135–180	$267 \pm 6 \pm 52$	400–800	$1.8 \pm 0.2 \pm 0.4$
180–225	$138 \pm 5 \pm 24$		
Additional jets: 2			
0–45	$92 \pm 3 \pm 17$	225–270	$50 \pm 2 \pm 9$
45–90	$210 \pm 5 \pm 37$	270–315	$29 \pm 2 \pm 6$
90–135	$196 \pm 4 \pm 35$	315–400	$10.6 \pm 1.0 \pm 1.7$
135–180	$136 \pm 4 \pm 25$	400–800	$1.1 \pm 0.2 \pm 0.2$
180–225	$82 \pm 3 \pm 17$		
Additional jets: ≥ 3			
0–45	$40 \pm 2 \pm 8$	225–270	$28 \pm 2 \pm 8$
45–90	$90 \pm 3 \pm 20$	270–315	$18 \pm 1 \pm 5$
90–135	$94 \pm 3 \pm 25$	315–400	$8.4 \pm 0.8 \pm 3.1$
135–180	$69 \pm 2 \pm 21$	400–800	$1.2 \pm 0.2 \pm 0.3$
180–225	$45 \pm 2 \pm 14$		

APPENDIX B: TABLES OF PARTICLE-LEVEL CROSS SECTIONS

TABLE XIII. Differential cross sections at parton level as a function of $p_T(\tilde{t}\bar{\tilde{t}})$ in bins of the number of additional jets. The values are shown together with their statistical and systematic uncertainties.

$p_T(\tilde{t}\bar{\tilde{t}})$ [GeV]	$\frac{d\sigma}{dp_T(\tilde{t}\bar{\tilde{t}})}$ [fb GeV ⁻¹]	$p_T(\tilde{t}\bar{\tilde{t}})$ [GeV]	$\frac{d\sigma}{dp_T(\tilde{t}\bar{\tilde{t}})}$ [fb GeV ⁻¹]
Additional jets: 0			
0–35	2220 ± 60 ± 530	140–200	14 ± 5 ± 6
35–80	420 ± 40 ± 210	200–500	0.1 ± 0.2 ± 0.1
80–140	50 ± 10 ± 40		
Additional jets: 1			
0–35	610 ± 40 ± 160	140–200	100 ± 10 ± 20
35–80	670 ± 30 ± 90	200–500	9 ± 1 ± 2
80–140	260 ± 20 ± 40		
Additional jets: 2			
0–35	150 ± 10 ± 40	140–200	68 ± 8 ± 12
35–80	240 ± 10 ± 60	200–500	18 ± 1 ± 3
80–140	180 ± 10 ± 40		
Additional jets: ≥ 3			
0–35	42 ± 6 ± 22	140–200	54 ± 6 ± 13
35–80	95 ± 8 ± 29	200–500	14.3 ± 0.8 ± 3.4
80–140	77 ± 6 ± 23		

TABLE XIV. Double-differential cross section at parton level as a function of $|y(t_h)|$ vs $p_T(t_h)$. The values are shown together with their statistical and systematic uncertainties.

$p_T(t_h)$ [GeV]	$\frac{d^2\sigma}{dp_T(t_h)d|y(t_h)|}$ [fb GeV ⁻¹]	$p_T(t_h)$ [GeV]	$\frac{d^2\sigma}{dp_T(t_h)d|y(t_h)|}$ [fb GeV ⁻¹]
$0 < |y(t_h)| < 0.5$			
0–45	370 ± 8 ± 74	225–270	149 ± 4 ± 19
45–90	830 ± 10 ± 120	270–315	81 ± 3 ± 11
90–135	770 ± 10 ± 80	315–400	36 ± 2 ± 6
135–180	493 ± 8 ± 59	400–800	4.4 ± 0.3 ± 0.6
180–225	268 ± 6 ± 36		
$0.5 < |y(t_h)| < 1$			
0–45	340 ± 7 ± 56	225–270	127 ± 4 ± 22
45–90	730 ± 10 ± 110	270–315	65 ± 3 ± 11
90–135	669 ± 10 ± 73	315–400	26 ± 1 ± 3
135–180	425 ± 8 ± 49	400–800	3.3 ± 0.3 ± 0.6
180–225	238 ± 6 ± 34		
$1 < |y(t_h)| < 1.5$			
0–45	278 ± 7 ± 44	225–270	88 ± 3 ± 11
45–90	600 ± 10 ± 70	270–315	48 ± 2 ± 8
90–135	528 ± 9 ± 65	315–400	19 ± 1 ± 3
135–180	334 ± 7 ± 46	400–800	1.5 ± 0.2 ± 0.2
180–225	173 ± 5 ± 25		
$1.5 < |y(t_h)| < 2.5$			
0–45	188 ± 7 ± 24	225–270	46 ± 2 ± 8
45–90	385 ± 9 ± 50	270–315	20 ± 1 ± 4
90–135	318 ± 7 ± 44	315–400	6.3 ± 0.6 ± 1.0
135–180	175 ± 5 ± 22	400–800	0.50 ± 0.09 ± 0.09
180–225	91 ± 3 ± 12		

TABLE XV. Double-differential cross section at parton level as a function of $M(\tilde{t}\bar{\tilde{t}})$ vs $|y(\tilde{t}\bar{\tilde{t}})|$. The values are shown together with their statistical and systematic uncertainties.

$|y(\tilde{t}\bar{\tilde{t}})|$	$\frac{d^2\sigma}{dM(\tilde{t}\bar{\tilde{t}})d|y(\tilde{t}\bar{\tilde{t}})|}$ [fb GeV ⁻¹]	$|y(\tilde{t}\bar{\tilde{t}})|$	$\frac{d^2\sigma}{dM(\tilde{t}\bar{\tilde{t}})d|y(\tilde{t}\bar{\tilde{t}})|}$ [fb GeV ⁻¹]
$300 < M(\tilde{t}\bar{\tilde{t}}) < 450$ GeV			
0–0.2	418 ± 10 ± 67	0.6–0.9	374 ± 7 ± 53
0.2–0.4	418 ± 8 ± 63	0.9–1.3	307 ± 7 ± 46
0.4–0.6	409 ± 8 ± 56	1.3–2.3	162 ± 5 ± 25
$450 < M(\tilde{t}\bar{\tilde{t}}) < 625$ GeV			
0–0.2	359 ± 7 ± 45	0.6–0.9	303 ± 6 ± 43
0.2–0.4	343 ± 6 ± 45	0.9–1.3	224 ± 5 ± 36
0.4–0.6	331 ± 7 ± 46	1.3–2.3	99 ± 3 ± 15
$625 < M(\tilde{t}\bar{\tilde{t}}) < 850$ GeV			
0–0.2	123 ± 4 ± 18	0.6–0.9	87 ± 3 ± 13
0.2–0.4	108 ± 3 ± 17	0.9–1.3	62 ± 3 ± 13
0.4–0.6	92 ± 3 ± 13	1.3–2.3	24 ± 2 ± 5
$850 < M(\tilde{t}\bar{\tilde{t}}) < 2000$ GeV			
0–0.2	10.0 ± 0.6 ± 1.5	0.6–0.9	6.9 ± 0.5 ± 0.8
0.2–0.4	10.1 ± 0.6 ± 1.4	0.9–1.3	3.7 ± 0.4 ± 0.5
0.4–0.6	9.1 ± 0.6 ± 1.5	1.3–2.3	1.0 ± 0.2 ± 0.2

TABLE XVI. Double-differential cross section at parton level as a function of $p_T(\tilde{t}\bar{\tilde{t}})$ vs $M(\tilde{t}\bar{\tilde{t}})$. The values are shown together with their statistical and systematic uncertainties.

$M(\tilde{t}\bar{\tilde{t}})$ [GeV]	$\frac{d^2\sigma}{dp_T(\tilde{t}\bar{\tilde{t}})dM(\tilde{t}\bar{\tilde{t}})}$ [fb GeV ⁻²]	$M(\tilde{t}\bar{\tilde{t}})$ [GeV]	$\frac{d^2\sigma}{dp_T(\tilde{t}\bar{\tilde{t}})dM(\tilde{t}\bar{\tilde{t}})}$ [fb GeV ⁻²]
$0 < p_T(\tilde{t}\bar{\tilde{t}}) < 35$ GeV			
300–375	4.8 ± 0.2 ± 2.0	625–740	2.18 ± 0.09 ± 0.63
375–450	13.7 ± 0.3 ± 3.0	740–850	0.92 ± 0.06 ± 0.18
450–530	8.5 ± 0.2 ± 3.8	850–1100	0.36 ± 0.03 ± 0.12
530–625	4.4 ± 0.1 ± 1.3	1100–2000	0.039 ± 0.005 ± 0.012
$35 < p_T(\tilde{t}\bar{\tilde{t}}) < 80$ GeV			
300–375	2.25 ± 0.07 ± 1.20	625–740	1.32 ± 0.04 ± 0.22
375–450	6.6 ± 0.1 ± 1.6	740–850	0.60 ± 0.03 ± 0.07
450–530	4.30 ± 0.08 ± 0.60	850–1100	0.23 ± 0.01 ± 0.03
530–625	2.53 ± 0.06 ± 0.29	1100–2000	0.022 ± 0.002 ± 0.005
$80 < p_T(\tilde{t}\bar{\tilde{t}}) < 140$ GeV			
300–375	0.76 ± 0.03 ± 0.30	625–740	0.51 ± 0.02 ± 0.07
375–450	2.24 ± 0.05 ± 0.50	740–850	0.25 ± 0.01 ± 0.04
450–530	1.52 ± 0.04 ± 0.19	850–1100	0.100 ± 0.008 ± 0.026
530–625	0.96 ± 0.03 ± 0.10	1100–2000	0.011 ± 0.002 ± 0.002
$140 < p_T(\tilde{t}\bar{\tilde{t}}) < 500$ GeV			
300–375	0.095 ± 0.005 ± 0.025	625–740	0.068 ± 0.003 ± 0.017
375–450	0.258 ± 0.008 ± 0.032	740–850	0.036 ± 0.002 ± 0.004
450–530	0.185 ± 0.006 ± 0.024	850–1100	0.016 ± 0.001 ± 0.003
530–625	0.122 ± 0.005 ± 0.034	1100–2000	0.0018 ± 0.0003 ± 0.0003

TABLE XVII. Differential cross section at particle level as a function of $p_T(t_h)$. The values are shown together with their statistical and systematic uncertainties.

$p_T(t_h)$ [GeV]	$\frac{d\sigma}{dp_T(t_h)}$ [fb GeV ⁻¹]	$p_T(t_h)$ [GeV]	$\frac{d\sigma}{dp_T(t_h)}$ [fb GeV ⁻¹]
0–45	$204 \pm 4 \pm 18$	225–270	$106 \pm 2 \pm 9$
45–90	$461 \pm 5 \pm 40$	270–315	$61 \pm 2 \pm 6$
90–135	$430 \pm 5 \pm 41$	315–400	$27.4 \pm 0.9 \pm 2.5$
135–180	$292 \pm 4 \pm 27$	400–800	$3.2 \pm 0.2 \pm 0.3$
180–225	$179 \pm 3 \pm 17$		

TABLE XVIII. Differential cross section at particle level as a function of $|y(t_h)|$. The values are shown together with their statistical and systematic uncertainties.

$|y(t_h)|$	$\frac{d\sigma}{d|y(t_h)|}$ [pb]	$|y(t_h)|$	$\frac{d\sigma}{d|y(t_h)|}$ [pb]
0–0.2	$61.3 \pm 0.7 \pm 5.2$	1–1.3	$38.6 \pm 0.4 \pm 3.7$
0.2–0.4	$59.4 \pm 0.6 \pm 4.9$	1.3–1.6	$27.8 \pm 0.4 \pm 3.1$
0.4–0.7	$55.1 \pm 0.5 \pm 4.7$	1.6–2.5	$7.3 \pm 0.1 \pm 0.8$
0.7,1	$47.6 \pm 0.5 \pm 4.2$		

TABLE XIX. Differential cross section at particle level as a function of $p_T(t_\ell)$. The values are shown together with their statistical and systematic uncertainties.

$p_T(t_\ell)$ [GeV]	$\frac{d\sigma}{dp_T(t_\ell)}$ [fb GeV ⁻¹]	$p_T(t_\ell)$ [GeV]	$\frac{d\sigma}{dp_T(t_\ell)}$ [fb GeV ⁻¹]
0–45	$185 \pm 3 \pm 17$	225–270	$113 \pm 2 \pm 9$
45–90	$425 \pm 4 \pm 41$	270–315	$67 \pm 2 \pm 5$
90–135	$429 \pm 4 \pm 41$	315–400	$30.6 \pm 0.9 \pm 2.4$
135–180	$310 \pm 4 \pm 28$	400–800	$3.7 \pm 0.2 \pm 0.4$
180–225	$194 \pm 3 \pm 16$		

TABLE XX. Differential cross section at particle level as a function of $|y(t_\ell)|$. The values are shown together with their statistical and systematic uncertainties.

$|y(t_\ell)|$	$\frac{d\sigma}{d|y(t_\ell)|}$ [pb]	$|y(t_\ell)|$	$\frac{d\sigma}{d|y(t_\ell)|}$ [pb]
0–0.2	$55.7 \pm 0.7 \pm 5.0$	1–1.3	$38.9 \pm 0.5 \pm 3.6$
0.2–0.4	$54.6 \pm 0.6 \pm 5.1$	1.3–1.6	$29.3 \pm 0.4 \pm 2.7$
0.4–0.7	$52.0 \pm 0.5 \pm 4.9$	1.6–2.5	$10.2 \pm 0.2 \pm 0.9$
0.7–1	$47.2 \pm 0.5 \pm 4.4$		

TABLE XXI. Differential cross section at particle level as a function of $p_T(\bar{t}\bar{t})$. The values are shown together with their statistical and systematic uncertainties.

$p_T(\bar{t}\bar{t})$ [GeV]	$\frac{d\sigma}{dp_T(\bar{t}\bar{t})}$ [fb GeV ⁻¹]	$p_T(\bar{t}\bar{t})$ [GeV]	$\frac{d\sigma}{dp_T(\bar{t}\bar{t})}$ [fb GeV ⁻¹]
0–35	$890 \pm 10 \pm 140$	140–200	$92 \pm 3 \pm 10$
35–80	$577 \pm 10 \pm 62$	200–500	$18.4 \pm 0.5 \pm 1.7$
80–140	$219 \pm 5 \pm 22$		

TABLE XXII. Differential cross section at particle level as a function of $M(\bar{t}\bar{t})$. The values are shown together with their statistical and systematic uncertainties.

$M(\bar{t}\bar{t})$ [GeV]	$\frac{d\sigma}{dM(\bar{t}\bar{t})}$ [fb GeV ⁻¹]	$M(\bar{t}\bar{t})$ [GeV]	$\frac{d\sigma}{dM(\bar{t}\bar{t})}$ [fb GeV ⁻¹]
300–375	$124 \pm 4 \pm 14$	625–740	$91 \pm 2 \pm 8$
375–450	$247 \pm 4 \pm 27$	740–850	$47 \pm 2 \pm 4$
450–530	$200 \pm 4 \pm 22$	850–1100	$22.3 \pm 0.8 \pm 2.1$
530–625	$144 \pm 3 \pm 13$	1100–2000	$2.7 \pm 0.2 \pm 0.4$

TABLE XXIII. Differential cross section at particle level as a function of $|y(\bar{t}\bar{t})|$. The values are shown together with their statistical and systematic uncertainties.

$|y(\bar{t}\bar{t})|$	$\frac{d\sigma}{d|y(\bar{t}\bar{t})|}$ [pb]	$|y(\bar{t}\bar{t})|$	$\frac{d\sigma}{d|y(\bar{t}\bar{t})|}$ [pb]
0–0.2	$76.2 \pm 0.9 \pm 6.6$	0.6–0.9	$55.0 \pm 0.6 \pm 4.9$
0.2–0.4	$71.8 \pm 0.7 \pm 6.3$	0.9–1.3	$35.8 \pm 0.5 \pm 3.5$
0.4–0.6	$66.1 \pm 0.7 \pm 6.1$	1.3–2.3	$7.7 \pm 0.2 \pm 0.8$

TABLE XXIV. Cross sections at particle level in bins of the number of additional jets. The values are shown together with their statistical and systematic uncertainties.

Additional jets	σ [pb]	Additional jets	σ [pb]
0	$39.9 \pm 0.4 \pm 3.0$	3	$3.8 \pm 0.1 \pm 0.6$
1	$25.6 \pm 0.3 \pm 2.7$	≥ 4	$1.75 \pm 0.07 \pm 0.36$
2	$10.6 \pm 0.2 \pm 1.3$		

TABLE XXV. Differential cross sections at particle level as a function of $p_T(t_h)$ in bins of the number of additional jets. The values are shown together with their statistical and systematic uncertainties.

$p_T(t_h)$ [GeV]	$\frac{d\sigma}{dp_T(t_h)}$ [fb GeV ⁻¹]	$p_T(t_h)$ [GeV]	$\frac{d\sigma}{dp_T(t_h)}$ [fb GeV ⁻¹]
Additional jets: 0			
0–45	$108 \pm 3 \pm 7$	225–270	$44 \pm 1 \pm 4$
45–90	$241 \pm 4 \pm 16$	270–315	$22.7 \pm 0.9 \pm 2.0$
90–135	$226 \pm 3 \pm 16$	315–400	$9.7 \pm 0.5 \pm 1.3$
135–180	$146 \pm 3 \pm 10$	400–800	$1.09 \pm 0.09 \pm 0.15$
180–225	$84 \pm 2 \pm 7$		
Additional jets: 1			
0–45	$60 \pm 1 \pm 7$	225–270	$34.8 \pm 0.9 \pm 3.6$
45–90	$136 \pm 2 \pm 16$	270–315	$20.9 \pm 0.7 \pm 2.6$
90–135	$129 \pm 2 \pm 13$	315–400	$9.4 \pm 0.4 \pm 0.8$
135–180	$92 \pm 1 \pm 9$	400–800	$1.06 \pm 0.08 \pm 0.14$
180–225	$57 \pm 1 \pm 6$		
Additional jets: 2			
0–45	$24.7 \pm 0.5 \pm 3.5$	225–270	$17.1 \pm 0.5 \pm 2.1$
45–90	$55.8 \pm 0.9 \pm 7.7$	270–315	$10.7 \pm 0.4 \pm 1.3$
90–135	$52.7 \pm 0.8 \pm 6.9$	315–400	$4.9 \pm 0.3 \pm 0.6$
135–180	$38.4 \pm 0.7 \pm 4.6$	400–800	$0.60 \pm 0.05 \pm 0.08$
180–225	$26.0 \pm 0.6 \pm 3.1$		
Additional jets: ≥ 3			
0–45	$11.6 \pm 0.3 \pm 2.0$	225–270	$9.4 \pm 0.4 \pm 1.4$
45–90	$25.9 \pm 0.6 \pm 4.4$	270–315	$6.5 \pm 0.3 \pm 1.0$
90–135	$26.0 \pm 0.6 \pm 4.3$	315–400	$3.5 \pm 0.2 \pm 0.6$
135–180	$19.2 \pm 0.5 \pm 2.8$	400–800	$0.47 \pm 0.05 \pm 0.07$
180–225	$13.5 \pm 0.4 \pm 1.8$		

TABLE XXVI. Differential cross sections at particle level as a function of $p_T(\bar{t}\bar{t})$ in bins of the number of additional jets. The values are shown together with their statistical and systematic uncertainties.

$p_T(\bar{t}\bar{t})$ [GeV]	$\frac{d\sigma}{dp_T(\bar{t}\bar{t})}$ [fb GeV ⁻¹]	$p_T(\bar{t}\bar{t})$ [GeV]	$\frac{d\sigma}{dp_T(\bar{t}\bar{t})}$ [fb GeV ⁻¹]
Additional jets: 0			
0–35	730 ± 10 ± 100	140–200	7 ± 1 ± 2
35–80	268 ± 8 ± 31	200–500	0.19 ± 0.09 ± 0.07
80–140	33 ± 3 ± 8		
Additional jets: 1			
0–35	118 ± 5 ± 19	140–200	45 ± 3 ± 5
35–80	222 ± 5 ± 26	200–500	6.6 ± 0.4 ± 0.7
80–140	112 ± 4 ± 12		
Additional jets: 2			
0–35	25 ± 2 ± 5	140–200	26 ± 2 ± 3
35–80	59 ± 3 ± 10	200–500	6.8 ± 0.4 ± 0.7
80–140	55 ± 2 ± 8		
Additional jets: ≥ 3			
0–35	8.1 ± 1.0 ± 2.0	140–200	17 ± 1 ± 4
35–80	23 ± 2 ± 5	200–500	5.4 ± 0.3 ± 0.8
80–140	22 ± 1 ± 4		

TABLE XXVII. Double-differential cross section at particle level as a function of $|y(t_h)|$ vs $p_T(t_h)$. The values are shown together with their statistical and systematic uncertainties.

$p_T(t_h)$ [GeV]	$\frac{d^2\sigma}{dp_T(t_h)d|y(t_h)|}$ [fb GeV ⁻¹]	$p_T(t_h)$ [GeV]	$\frac{d^2\sigma}{dp_T(t_h)d|y(t_h)|}$ [fb GeV ⁻¹]
0 < $|y(t_h)|$ < 0.5			
0–45	146 ± 2 ± 12	225–270	78 ± 2 ± 6
45–90	330 ± 4 ± 28	270–315	46 ± 1 ± 4
90–135	316 ± 4 ± 26	315–400	21.8 ± 0.8 ± 2.0
135–180	217 ± 3 ± 18	400–800	2.7 ± 0.2 ± 0.3
180–225	129 ± 2 ± 11		
0.5 < $|y(t_h)|$ < 1			
0–45	126 ± 2 ± 13	225–270	63 ± 2 ± 6
45–90	281 ± 3 ± 25	270–315	36 ± 1 ± 3
90–135	267 ± 3 ± 23	315–400	16.4 ± 0.7 ± 1.4
135–180	182 ± 3 ± 15	400–800	2.2 ± 0.1 ± 0.3
180–225	112 ± 2 ± 10		
1 < $|y(t_h)|$ < 1.5			
0–45	88 ± 2 ± 9	225–270	44 ± 1 ± 4
45–90	198 ± 3 ± 21	270–315	25.3 ± 1.0 ± 2.3
90–135	186 ± 3 ± 18	315–400	11.1 ± 0.6 ± 1.2
135–180	130 ± 2 ± 12	400–800	0.99 ± 0.09 ± 0.11
180–225	77 ± 2 ± 7		
1.5 < $|y(t_h)|$ < 2.5			
0–45	21.9 ± 0.8 ± 3.3	225–270	12.9 ± 0.5 ± 1.4
45–90	49 ± 1 ± 6	270–315	7.0 ± 0.4 ± 0.8
90–135	48 ± 1 ± 5	315–400	2.9 ± 0.2 ± 0.3
135–180	32.2 ± 0.9 ± 3.2	400–800	0.25 ± 0.03 ± 0.04
180–225	21.3 ± 0.7 ± 2.0		

TABLE XXVIII. Double-differential cross section at particle level as a function of $M(\bar{t}\bar{t})$ vs $|y(\bar{t}\bar{t})|$. The values are shown together with their statistical and systematic uncertainties.

$|y(\bar{t}\bar{t})|$	$\frac{d^2\sigma}{dM(\bar{t}\bar{t})d|y(\bar{t}\bar{t})|}$ [fb GeV ⁻¹]	$|y(\bar{t}\bar{t})|$	$\frac{d^2\sigma}{dM(\bar{t}\bar{t})d|y(\bar{t}\bar{t})|}$ [fb GeV ⁻¹]
300 < $M(\bar{t}\bar{t})$ < 450 GeV			
0–0.2	143 ± 3 ± 12	0.6–0.9	124 ± 3 ± 11
0.2–0.4	142 ± 3 ± 12	0.9–1.3	96 ± 2 ± 9
0.4–0.6	140 ± 3 ± 12	1.3–2.3	25.7 ± 0.9 ± 2.5
450 < $M(\bar{t}\bar{t})$ < 625 GeV			
0–0.2	158 ± 3 ± 15	0.6–0.9	118 ± 2 ± 12
0.2–0.4	148 ± 3 ± 15	0.9–1.3	75 ± 2 ± 9
0.4–0.6	142 ± 3 ± 14	1.3–2.3	15.5 ± 0.6 ± 1.7
625 < $M(\bar{t}\bar{t})$ < 850 GeV			
0–0.2	77 ± 2 ± 6	0.6–0.9	47 ± 1 ± 4
0.2–0.4	67 ± 2 ± 6	0.9–1.3	27 ± 1 ± 3
0.4–0.6	57 ± 2 ± 5	1.3–2.3	4.3 ± 0.3 ± 0.4
850 < $M(\bar{t}\bar{t})$ < 2000 GeV			
0–0.2	8.4 ± 0.4 ± 0.9	0.6–0.9	4.7 ± 0.3 ± 0.4
0.2–0.4	8.5 ± 0.4 ± 1.0	0.9–1.3	1.9 ± 0.1 ± 0.2
0.4–0.6	6.7 ± 0.3 ± 0.7	1.3–2.3	0.20 ± 0.03 ± 0.03

TABLE XXIX. Double-differential cross section at particle level as a function of $p_T(\bar{t}\bar{t})$ vs $M(\bar{t}\bar{t})$. The values are shown together with their statistical and systematic uncertainties.

$M(\bar{t}\bar{t})$ [GeV]	$\frac{d^2\sigma}{dp_T(\bar{t}\bar{t})dM(\bar{t}\bar{t})}$ [fb GeV ⁻²]	$M(\bar{t}\bar{t})$ [GeV]	$\frac{d^2\sigma}{dp_T(\bar{t}\bar{t})dM(\bar{t}\bar{t})}$ [fb GeV ⁻²]
0 < $p_T(\bar{t}\bar{t})$ < 35 GeV			
300–375	1.44 ± 0.05 ± 0.09	625–740	0.88 ± 0.02 ± 0.11
375–450	2.85 ± 0.06 ± 0.41	740–850	0.48 ± 0.02 ± 0.05
450–530	2.26 ± 0.05 ± 0.40	850–1100	0.215 ± 0.010 ± 0.040
530–625	1.47 ± 0.03 ± 0.22	1100–2000	0.030 ± 0.003 ± 0.012
35 < $p_T(\bar{t}\bar{t})$ < 80 GeV			
300–375	0.89 ± 0.02 ± 0.09	625–740	0.66 ± 0.01 ± 0.06
375–450	1.76 ± 0.03 ± 0.20	740–850	0.36 ± 0.01 ± 0.03
450–530	1.44 ± 0.02 ± 0.16	850–1100	0.158 ± 0.006 ± 0.020
530–625	1.03 ± 0.02 ± 0.09	1100–2000	0.018 ± 0.001 ± 0.004
80 < $p_T(\bar{t}\bar{t})$ < 140 GeV			
300–375	0.31 ± 0.01 ± 0.03	625–740	0.249 ± 0.007 ± 0.021
375–450	0.67 ± 0.02 ± 0.08	740–850	0.137 ± 0.005 ± 0.016
450–530	0.55 ± 0.01 ± 0.06	850–1100	0.059 ± 0.003 ± 0.007
530–625	0.395 ± 0.010 ± 0.036	1100–2000	0.0066 ± 0.0007 ± 0.0018
140 < $p_T(\bar{t}\bar{t})$ < 500 GeV			
300–375	0.035 ± 0.002 ± 0.007	625–740	0.039 ± 0.001 ± 0.004
375–450	0.081 ± 0.002 ± 0.009	740–850	0.022 ± 0.001 ± 0.003
450–530	0.077 ± 0.002 ± 0.008	850–1100	0.0107 ± 0.0006 ± 0.0009
530–625	0.061 ± 0.002 ± 0.008	1100–2000	0.0016 ± 0.0002 ± 0.0002

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